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HYDROGEN FUEL AS A SUBSTITUTE FOR FOSSIL FUELS

by

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TABLE OF CONTENTS

Executive Summary

1. Overview of present and predicted future environmental problems associated with fossil fuel use 1

    1.1 Urban air pollution 1

    1.2 Acid deposition 7

    1.3 Greenhouse gases 14

        1.3.1 Carbon dioxide 14
        1.3.2 Other greenhouse gases 39
        1.3.3 Summary of climatic and physical impacts of greenhouse gases 43

    1.4 Potential effects of fossil fuel use on stratospheric ozone 44

    1.5 Policy options and constraints as conventional liquid fuels are depleted 44

    1.6 Strategies for limiting CO_2 increases 46

2. Potential role of hydrogen in solving environmental problems 50

    2.1 Environmental and health benefits of a hydrogen-based energy system 50

    2.2 Production of hydrogen 53

        2.2.1 Fossil fuel sources 53
        2.2.2 Non-fossil fuel sources 53

    2.3 Uses of hydrogen 58

        2.3.1 Current uses 58
        2.3.2 Future uses 59

    2.4 Safety of hydrogen 68

    2.5 Hydrogen distribution and storage 68

    2.6 Economics of hydrogen 69

    2.7 Environmental costs of a hydrogen economy 72

3.0 Importance of energy conservation in the transition to a hydrogen economy 77

4.0 Emerging policy issues 80

5.0 Summary 84

EXECUTIVE SUMMARY

The use of fossil fuels for the generation of electricity, and to provide energy for domestic heating, transportation, and industrial uses, causes three major environmental problems. They are (1) urban air pollution, (2) acid deposition, and (3) the increase in atmospheric CO_2 and other greenhouse gases. Urban air quality is a serious health and environmental problem in many of the world's major cities. Acid deposition poses a major environmental threat and human health hazard on a regional and subcontinental scale. The continuing build-up of CO_2 in the atmosphere will affect climate on a global scale and will be effectively irreversible if it is not controlled.

The primary urban air pollutants are sulphur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), ozone (O_3), suspended particulates including polycyclic aromatic compounds (PAH's), and lead. The SO_2 comes mainly from the primary production and processing of metals, petroleum refining and the combustion of sulphur-containing fuels such as coal and oil. Gasoline-powered vehicles are the dominant sources of NO_x and airborne lead. Diesel fueled vehicles are the main sources of suspended particulates exclusive of PAH's, whereas coal and fuel wood combustion are major sources of PAH's. Ozone is not emitted directly but is produced by photochemical reactions in the atmosphere with NO_x and hydrocarbons. Urban air pollutants reduce both breathing functions and resistance to lung infections; there is considerable debate, however, as to whether pollution levels found in North American cities lead to increased mortality. Estimates of the number of deaths in the United States from urban air pollution range from essentially 0 to over 50,000 per year. There is agreement that pollution levels only 3-4 times that found in American cities, and thus characteristic of some of the world's most polluted cities, can cause significant increases in mortality. There is also growing field and laboratory evidence that ozone concentrations typical of the eastern United States may be causing significant reductions in growth of trees and agricultural crops. Current measures to reduce automobile emissions rely on catalytic converters which make use of precious metals such as platinum, palladium, and rhodium, and tend to be used only in the industrialized countries. Such measures can only be palliative, not a cure. Due to the vagaries of automobile maintenance and the impracticality of universal testing, the actual percentage reduction falls well short of design objectives and emission standards. Pushing this strategy towards greater actual reductions will result in greater costs for smaller marginal returns - a characteristic of most palliative measures because they do not go to the root of the problem.

The ineffectiveness of palliative measures is even more evident in the case of acid deposition. Current plans to reduce SO_2 emission in Canada by half by 1994 compared to 1980 emissions, even if implemented in the United States as well, would improve but not eliminate the acid deposition problem. The same would be true even if all the major SO_2 emitting countries in Western and Eastern Europe were to reduce their emissions by half. First, for many sensitive regions reductions of SO_2 deposition rates by much more then a factor of two are needed; second, even in less sensitive regions reductions by a factor of two may still have longterm effects, and third, NO_x emissions from automobiles also contribute to acid deposition. Although present plans or proposals for emission reductions will reduce the rate of deterioration in many areas or delay irreversible deterioration, implementation of such plans in most instances requires either a switch to low-sulphur coal and removal of SO_2 from flue gases. Supplies of low sulphur coal are limited, and removal of SO_2 from flue gases requires significant quantities of calcium carbonate and will create major disposal problems for the resultant calcium sulphate. These strategies, although urgently needed in the short term, do not constitute a long term solution to the acid deposition problem. A complete longterm solution to the acid deposition problem in North America, Europe, and elsewhere almost certainly requires a significant reduction in total fossil fuel use.

The continuing increase of atmospheric CO_2 will affect climate on a global scale and will be largely irreversible. Associated with climatic change would be a rise of sea level, which could be about 1-2 m for a CO_2 doubling but 5 m more if the West Antarctic ice cap disintegrates. Recoverable fossil fuel reserves are large enough to increase atmospheric CO_2 by a factor of 3-11. Significant climatic changes would be associated even with a CO_2 doubling, including a likely reduction in summer soil moisture and increased incidence of drought in many of the world's major food producing regions. It is possible that the net effect of a CO_2 doubling could be positive to Mankind as a whole, but it is also clear that large CO_2 increases (or even a CO_2 doubling) could have catastrophic consequences, with the risk increasing with increasing CO_2. Given that other greenhouse gases are also increasing whose cumulative effect might be comparable to that of CO_2 alone, the actual CO_2 increase must be limited to much less than a doubling in order to have the equivalent of no more than a CO_2 doubling. Furthermore, positive carbon cycle feedbacks exist which might amplify any anthropogenic CO_2 increases. If the equivalent of a CO_2 doubling (from 300 ppmv to 600 ppmv) is regarded as an acceptable upper limit, than using more than about 10-30 percent of the recoverable fossil fuel reserves is unacceptable on climatic grounds alone. If other greenhouse gases continue to increase, the CO_2 concentration should be kept to perhaps 500 ppmv or less in order to have the equivalent effect of a CO_2 doubling, and Mankind will be restricted to using an even smaller fraction of the remaining recoverable fossil fuel resources. Burning the remaining recoverable liquid fuels would increase atmospheric CO_2 by only about 15 - 26 percent. Thus, the main determinant of future atmospheric CO_2 amounts will be the extent to which solid fuels are used. To limit the atmospheric greenhouse effect to the equivalent of a CO_2 doubling requires phasing in non-fossil fuel energy sources as liquid fuels are depleted, rather than undertaking massive development of synthetic liquid fuels from fossil fuels. At the same time we must shift away from coal as an energy source for generating electricity. This process should begin by the turn of the century in order to avoid more than an equivalent CO_2 doubling, but can be done gradually over a period of several decades. The research needed to develop a comprehensive global plan for phasing out fossil fuels, and the evolution of the plan itself, must start immediately.

Hydrogen fuel derived from off-peak hydro-electric power, nuclear energy, and renewable energy sources such as solar, wind, and ocean thermal energy provides an ideal solution to the environmental problems outlined above as the only products of its use are energy and water (and in some cases minor amounts of NO_x). Energy can be stored as hydrogen and thus overcomes the major limitation of electricity - its inability to be stored. Hydrogen would thus solve the problem of supply-demand mismatch which currently severely restricts the usefulness of renewable energy sources such as solar and wind energy. Hydrogen could be used to fly airplanes, power automobiles, and generate electricity, as well as for space heating and as a feedstock in a number of industrial processes where it is currently not used. In all or almost all applications, hydrogen fuel can be used more efficiently than conventional fossil fuels, and in some instances several times more efficiently. A number of technical problems associated with replacing fossil fuels with hydrogen fuel currently exist but should be easily solvable. Emerging technologies such as glass microsphere storage of hydrogen, magnetic liquefaction, multi-band solar cells, high temperature water vapour electrolysis, and laminar flow control in hydrogen fueled aircraft, and further advances in catalytic combustion and fuel cells, demonstrate the tremendous potential of an integrated hydrogen-renewable energy system. On purely economic grounds, hydrogen fuels derived from renewables will likely be competitive with fossil fuels within the next few decades or less, even without considering the many externalities associated with fossil fuel use.

The three environmental problems of urban air pollution, acid rain, and the buildup of greenhouse gases all have a common cause - our overwhelming reliance on fossil fuels for energy- and hence are linked and interdependent. For this reason, some attempts or proposals to reduce individual problems, on a piecemeal basis, may make the other problems worse. Examples include use of catalytic converters to reduce NO_x emissions which at the same time increase emissions of N_2O - a strong greenhouse gas, and proposals to reduce the CO_2 buildup by removing CO_2 from the flue gases of coal-fired generating plants, which increases primary energy demand and hence coal consumption and the suite of environmental problems, including acid rain, associated with the use of coal. Simultaneous resolution of all three environmental problems enumerated above requires going directly to the root cause of these problems and dramatically phasing down the use of fossil fuels.

Given the seriousness of the environmental problems associated with our current reliance on fossil fuels, the long time (several decades) required to phase in a new hydrogen based energy system, and the difficulty of obtaining global agreement on a global strategy to stabilize the CO_2 concentration at some level below a doubling, it is of the utmost urgence that the technical feasibility and economics of hydrogen fuel generation and use be demonstrated as soon and as fully as possible through substantially increased research funding.

1. OVERVIEW OF PRESENT AND PROJECTED FUTURE ENVIRONMENTAL PROBLEMS ASSOCIATED WITH FOSSIL FUEL USE

1.1 Urban Air Pollution

The primary emissions from fossil fuel burning which have an effect on human health are sulphur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), suspended particulates and reactive hydrocarbons, and various heavy metals. Ozone (O_3) is not directly emitted by fossil fuel burning, but is produced photochemically from NO_x and reactive hydrocarbons. Lead has been used as an additive in gasoline and consequently has been emitted to the atmosphere. Since such emissions are not necessary consequences of fossil fuel use, and some countries have recently taken measures to completely phase out the use of lead in automobile fuel, it will not be discussed further here. The main sources of SO_2 are the primary production of copper and nickel, the combustion of sulphur-containing fuels such as coal, natural gas processing, iron ore processing, and petroleum refining. Gasoline powered vehicles are the dominant sources of NO_x and CO. The most important anthropogenic suspended particulate sources affecting urban environments in most Western countries are diesel fueled vehicles. Ozone is produced by photochemical reactions under conditions of strong sunlight on hydrocarbons and NO_x, whose main sources are gasoline and diesel powered transportation and residential, commercial, and industrial fuel combustion.

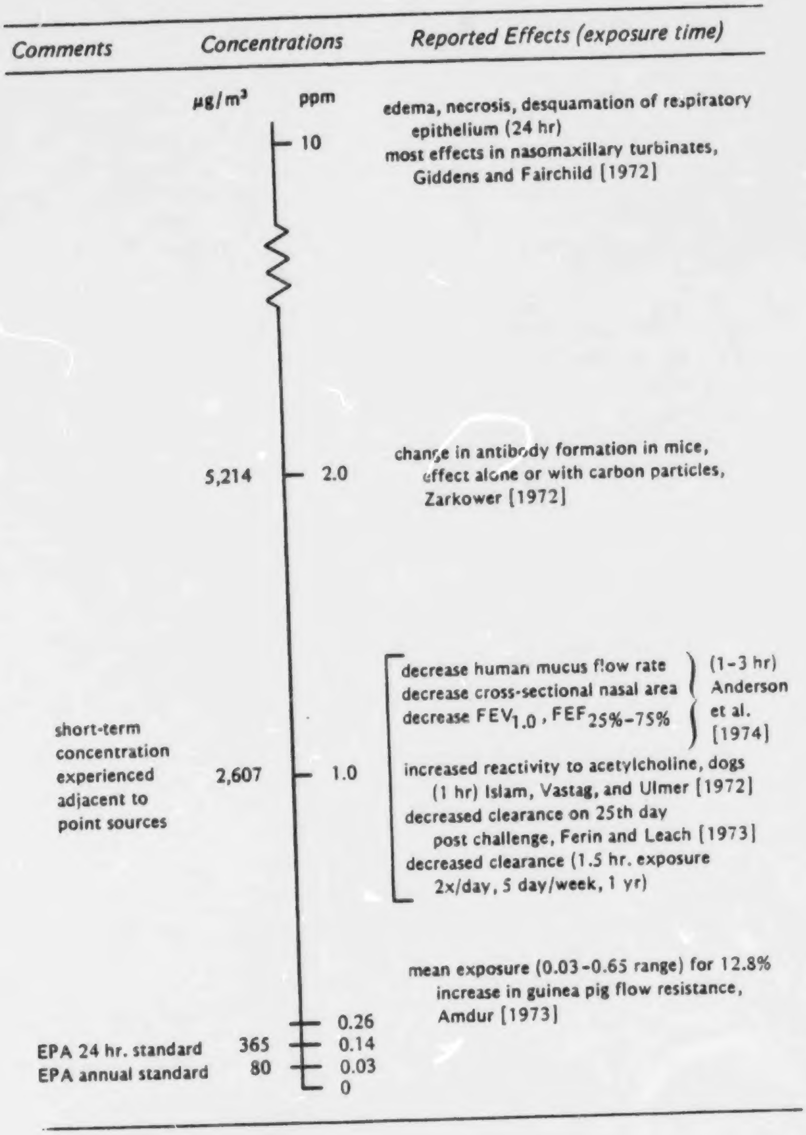
Assessments of the impact on human health of air pollution have been based on (1) epidemiological studies, in which mortality and disease statistics are compared between populations exposed to different pollution levels, or for the same population through time as pollution level varies; (2) controlled experiments with animals; and (3) controlled experiments with human volunteers. There are major uncertainties associated with each of these methods and, consequently, there is considerable debate and disagreement concerning the magnitude of human health effects. Part of the disagreement is linked to the controversy over whether or not a threshold exists for health effects of air pollution. As two examples of the range of opinion, Wilson et al (1980) summarize evidence suggesting that 50,000 Americans die each year as a result of air pollution effects; this estimate was obtained by using SO_x (SO_2 plus H_2SO_4 aerosols derived from SO_2) as a surrogate for all other pollutants and assuming a health hazard of 3.5 deaths per 100,000 persons per μg of SO_x exposure. Jaeger (1982), on the other hand, concludes that levels of SO_2 presently found in American cities, including the most polluted, are so low that their effect on health is questionable or marginal. Jaeger (1982) does stress, however, that SO_2 levels only 3-4 times higher than present levels in American cities can, especially when combined with high particulate levels and high humidity, cause catastrophic episodes of increased mortality.

Tables 1, 2, and 3 are taken from Wilson et al (1980) and summarize reported health effects of SO_2, NO_2, and O_3 acting alone. There is growing evidence, however, that SO_2 and particulates or SO_2 and O_3 act synergistically, so that the net effect of simultaneous exposure to these pairs of pollutants is greater than the sum of the effects associated with exposure to each pollutant separately (Hackney et al 1979; Wilson et al 1980). Diet can alter by several orders of magnitude the response of test animals to pollutants, but few animals used for testing the effects of pollutants have been rendered deficient or marginal in vitamins or minerals known to be lacking in human populations (Menzel, 1979). For example, vitamin E deficiency, common in the United States, increases the toxicity of O_3 and NO_2 pollutants. On the other hand, there is evidence of an adaptive increase in resistance of humans to O_3 (Hackney et al 1979).

The known health effects of the common urban air pollutants can be classified as (1) interference with breathing mechanisms, and (2) decreased lung resistance to infectious diseases. Children, the elderly, those with pre-existing lung ailments, and smokers are most susceptible to the effects of air pollution. According to Gardner (1982), high concentrations of pollutants for a brief exposure period are more hazardous with respect to disease resistance than the same integrated exposure but over a longer period of time. This is because only a short breakdown (on the order of a few hours) of defense mechanisms is required to allow invading bacteria to multiply to uncontrollable numbers. With regard to resistance to infection, Cd and O_3 appear to be the worst metallic and gaseous airborne pollutants (Gardner, 1982).

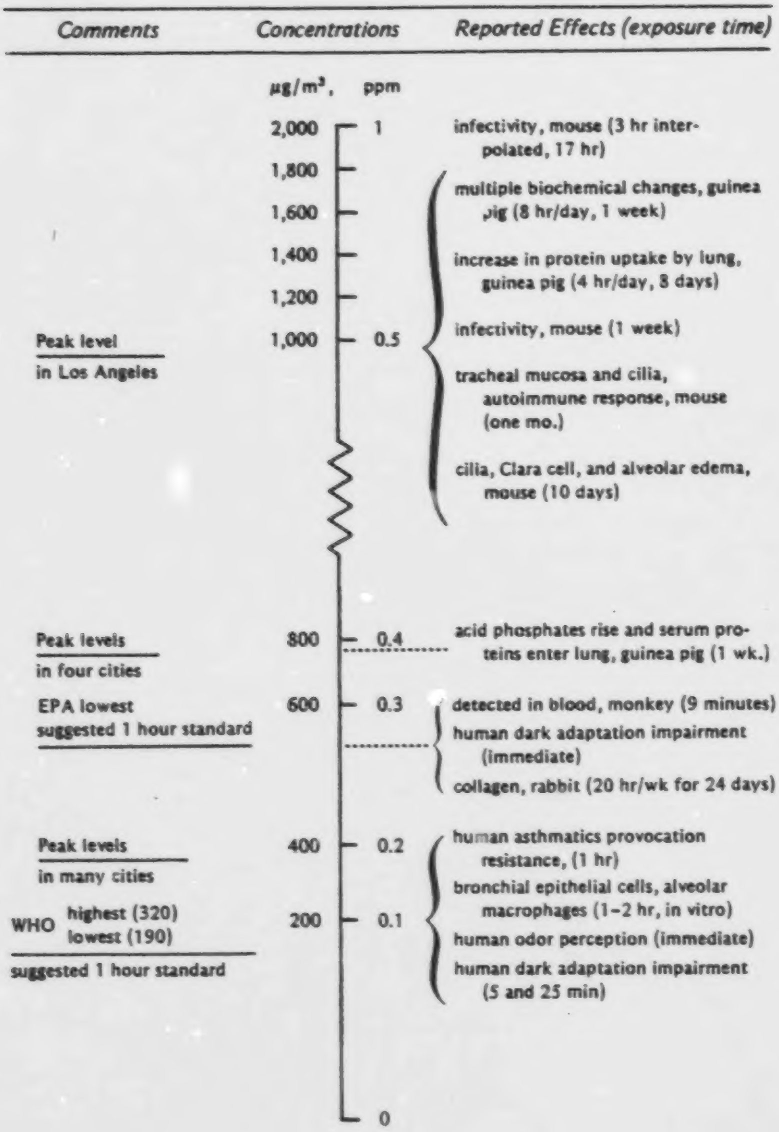
Particulate organic matter (POM) is generally produced when fossil fuels are burned, as a result of incomplete combustion. The most important POM's are polycyclic aromatic hydrocarbons (PAH), as many are known to be carcinogenic in animals or humans. Usually only one PAH, benzo (α) pyrene, is measured and used as a rough indicator of the overall level of PAH. Table 4, taken from Wilson et al (1982), lists sources of benzo (α) pyrene in the United States. Coal and wood burning are major sources of PAH's, with large coal-fired generating plants (as used in the developed world) emitting very little PAH's per unit of fuel consumed and hand-fired, residential combustion of coal (as used in parts of the third world) emitting 100,000 times more PAH's per unit of fuel consumed. In spite of the fact that most coal in the United States is used in large power plants, PAH's may be responsible for 1000 cancer deaths per year in the United States (Wilson et al, 1982). Per capita cancer deaths in countries such as China, where coal is extensively used in residential applications (Zweig, 1987), could be several orders of magnitude higher.

With regard to heavy metals, which are released through combustion of fossil fuels as well as through industrial



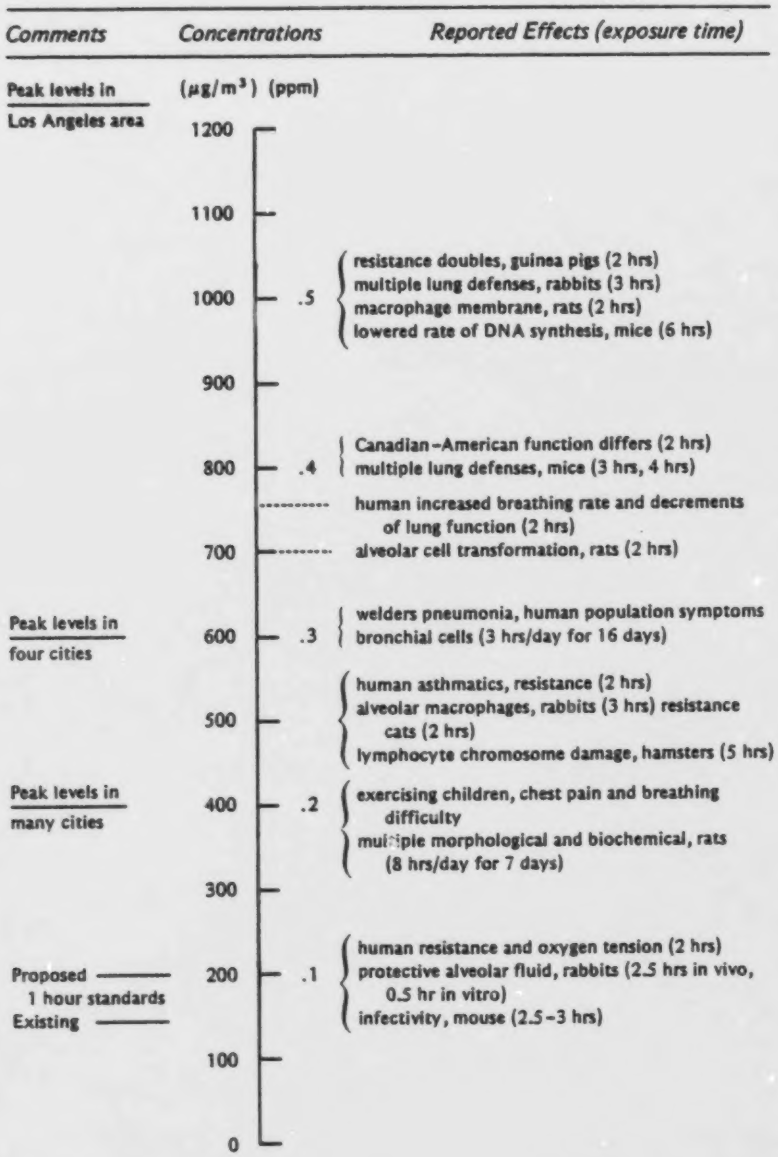
Comments	Concentrations		Reported Effects (exposure time)
	µg/m³	ppm	
		10	edema, necrosis, desquamation of respiratory epithelium (24 hr) most effects in nasomaxillary turbinates, Giddens and Fairchild [1972]
	5,214	2.0	change in antibody formation in mice, effect alone or with carbon particles, Zarkower [1972]
short-term concentration experienced adjacent to point sources	2,607	1.0	decrease human mucus flow rate decrease cross-sectional nasal area decrease $FEV_{1.0}$, $FEF_{25\%-75\%}$ (1-3 hr) Anderson et al. [1974] increased reactivity to acetylcholine, dogs (1 hr) Islam, Vastag, and Ulmer [1972] decreased clearance on 25th day post challenge, Ferin and Leach [1973] decreased clearance (1.5 hr. exposure 2x/day, 5 day/week, 1 yr)
		0.26	mean exposure (0.03-0.65 range) for 12.8% increase in guinea pig flow resistance, Amdur [1973]
EPA 24 hr. standard	365	0.14	
EPA annual standard	80	0.03	
		0	

Table 1. Health effects of SO_2 (source: Wilson et al 1980).



Comments	Concentrations µg/m³,	ppm	Reported Effects (exposure time)
	2,000	1	infectivity, mouse (3 hr interpolated, 17 hr)
	1,800		
	1,600		
	1,400		
	1,200		
Peak level in Los Angeles	1,000	0.5	multiple biochemical changes, guinea pig (8 hr/day, 1 week) increase in protein uptake by lung, guinea pig (4 hr/day, 8 days) infectivity, mouse (1 week) tracheal mucosa and cilia, autoimmune response, mouse (one mo.) cilia, Clara cell, and alveolar edema, mouse (10 days)
Peak levels in four cities	800	0.4	acid phosphates rise and serum proteins enter lung, guinea pig (1 wk.)
EPA lowest suggested 1 hour standard	600	0.3	detected in blood, monkey (9 minutes)
			human dark adaptation impairment (immediate) collagen, rabbit (20 hr/wk for 24 days)
Peak levels in many cities	400	0.2	
WHO highest (320) lowest (190) suggested 1 hour standard	200	0.1	human asthmatics provocation resistance, (1 hr) bronchial epithelial cells, alveolar macrophages (1-2 hr, in vitro) human odor perception (immediate) human dark adaptation impairment (5 and 25 min)
		0	

Table 2. Health effects of NO_2 (source: Wilson et al 1980).



Comments	Concentrations ($\mu g/m^3$)	(ppm)	Reported Effects (exposure time)
Peak levels in Los Angeles area	1200		
	1100		
	1000	.5	resistance doubles, guinea pigs (2 hrs) multiple lung defenses, rabbits (3 hrs) macrophage membrane, rats (2 hrs) lowered rate of DNA synthesis, mice (6 hrs)
	900		
	800	.4	Canadian-American function differs (2 hrs) multiple lung defenses, mice (3 hrs, 4 hrs)
			human increased breathing rate and decrements of lung function (2 hrs)
	700		alveolar cell transformation, rats (2 hrs)
Peak levels in four cities	600	.3	welders pneumonia, human population symptoms bronchial cells (3 hrs/day for 16 days)
	500		human asthmatics, resistance (2 hrs) alveolar macrophages, rabbits (3 hrs) resistance cats (2 hrs) lymphocyte chromosome damage, hamsters (5 hrs)
Peak levels in many cities	400	.2	exercising children, chest pain and breathing difficulty multiple morphological and biochemical, rats (8 hrs/day for 7 days)
	300		
Proposed 1 hour standards Existing	200	.1	human resistance and oxygen tension (2 hrs) protective alveolar fluid, rabbits (2.5 hrs in vivo, 0.5 hr in vitro) infectivity, mouse (2.5-3 hrs)
	100		
	0		

Table 3. Health effects of O_3 (source: Wilson et al 1980).

processes, Wilson et al (1982) state that, "high concentrations of arsenic, nickel, and chromium have been accused of causing lung cancer, but of these only arsenic has been accused of causing cancer outside the workplace [in the United States], and then only near smelters". As with other pollutants, the effects of heavy metals at existing concentrations are a subject of debate.

In most cities automobiles are the single largest source of air pollution. Automobile emission regulations have become increasingly strict in the United States and Canada. Compared to 1987 emission standards, emission standards for automobiles sold in Canada beginning with the 1988 model year will require about 3 times less NO_x, 5 times less hydrocarbons, and 8 times less CO per unit distance driven, which will make Canadian standards comparable to current American standards and will tend to lead to an improvement in urban air quality. Most other countries have less stringent emission standards, and poor countries generally have none at all. All except the poorest countries could probably strengthen their emission standards to those in effect in the United States and Canada if they wished. However, failure to keep automobiles properly tuned, so that they meet emission standards at the time of manufacture, or significant increases in the use of the automobile, could partly offset the effect of reduced emissions. There is a tendency for the ratio of actual emissions to emissions at the time of manufacture to increase as standards are tightened (Taylor, 1979). Furthermore, current strategies to reduce urban air pollution rely on catalytic converters, which in turn make use of platinum, palladium, and rhodium. Most developed countries rely extensively on third world sources for these materials.

In addition to the effect of urban air pollution on urban dwellers, there is growing concern about the effects of air pollution from urban centers on the agricultural productivity of the surrounding farmland. Ozone alone is recognized as a serious impediment to agricultural production downwind of many urban centers, with estimated O_3 damage to U.S. crops ranging from $1.7 billion to $3.6 billion per year (Wetstone and Rosencranz, 1983). There is also evidence that ozone concentrations typical of the eastern U.S. may be causing reductions in the growth rate of tree species (Reich and Amundson, 1985; Wang et al 1986).

In summary, there is general agreement that urban air pollution in major North American cities is responsible for a number of breathing impediments and decreased resistance to lung infections. There is a wide divergence of opinion as to whether or not North American levels of air pollution are responsible for increased mortality; estimates of the number annual deaths attributable to air pollution in the United States range from 0 to over 50,000. Even if North American or European levels of air pollution are not directly linked to increased mortality,

Table 4. Sources of benzo (α) pyrene in the United States (source: Wilson et al 1980).

	Emission Factor Lbs. BαP/10^4 Ton Fuel	Total Emission Tons BαP/Year (1967)
Coal		
hand-fired (residential)	1100-2200	420
intermediate	0.01-0.03	10
steam power	0.01-0.3	1
Oil	0.1-1	2
Gas	-	2
Wood	20-1000	40
Incineration		33
Open burning		
forest and agriculture		140
coal refuse		340
miscellaneous		74

existing air pollution levels cause considerable human discomfort and have adverse chronic health effects. In many third world cities, such as Mexico city or Bangkok, pollution levels are noticeably higher than in much of the developed world and are certain to take a major toll in human health and life. In China widespread use of coal for electricity generation near cities and for cooking and heating within cities has lead to significant urban air pollution problems and significant adverse health effects (Zweig, 1987).

1.2 Acid deposition

Acid deposition refers to the deposition of acids at the earth's surface both dissolved in rainwater (acid rain) and as dry particles (dry deposition), and is an environmental problem of great concern in North America, Europe, and, more recently, in China. Among the effects of acid deposition which have been identified or are suspected are: (1) acidification of lakes with concurrent reductions in fish species diversity and richness and appearance of undesirable organisms; (2) loss of Atlantic salmon

Table 5. National SO_2 emissions, 10^6 metric tons SO_2/year. (source: Wetstone and Rosencranz, 1983).

Northwest Europe	
Austria	0.43
Belgium	0.73
Denmark	0.46
Finland	0.54
France	3.40
Ireland	0.17
Luxembourg	0.05
Netherlands	0.51
Norway	0.15
Sweden	0.25
Switzerland	0.12
United Kingdom	4.70
West Germany	3.50
Total	15.04
Northeast Europe	
Czechoslovakia	3.37
East Germany	4.00
Hungary	1.50
Poland	3.00
USSR	25.50
Total	37.37
North America	
Canada	4.77
United States	24.10
Total	28.87
Grand Total	81.28

breeding habitats in Nova Scotia (Canada); (3) acidification of groundwater supplies; (4) reductions in forest productivity in eastern North American and especially in Europe, and a decline in sugar maple in Canada; (5) human health effects associated with sulphate particulates and, potentially, through increases in the concentrations of toxic components by leaching materials from waterbeds and sediments and by corroding materials used to distribute and store water; and (6) increased deterioration of buildings, particularly by SO_2. The economic cost alone of these effects, if unchecked, would be staggering.

The main acidifying pollutants are sulphur dioxide (SO_2), which is released from combustion of fossil fuels (coal in particular and fuel oil to a smaller extent) and non-ferrous smelting, and NO_x, which is produced from N_2 and O_2 in the air as a result of high temperature combustion. Sulphur dioxide is regarded as the more important source of acid deposition, and measures aimed at reducing acid deposition have involved reductions of SO_2 emissions. Table 5 summarizes estimates of SO_2 emissions from various countries corresponding to about the year 1980, while Table 6 gives a breakdown of the sources of both SO_2 and NO_x emissions in Canada and the United States. It is readily seen that almost half the SO_2 emissions in Canada come from non-ferrous smelting, whereas two-thirds of the emissions in the United States come from thermal power generation. In the case of NO_x, almost two-thirds of the emissions in Canada come from transportation but only about 38 % comes from transportation in the United States, the difference being largely a result of greater emissions from thermal power generation in the United States. The United Kingdom is the single largest emitter of SO_2 in Western Europe, largely from coal-fired thermal generating plants, which provide 70 percent of the U.K.'s electricity.

In June 1982 at the Stockholm Conference on Acidification of the Human Environment, leading experts from 20 nations of Europe and North America agreed that acidification of sensitive lakes could be prevented if total S deposition is kept below 0.5 gm S m^{-2} yr^{-1} (corresponding to about 15 kg sulfate ha^{-1} yr^{-1}). Figure 1 shows sulfate deposition rates over North America for the years 1981, 1982, and 1983, while Figure 2 compares precipitation sulfate levels in North America and Europe. Sulfate deposition rates exceed 20 kg ha^{-1} yr^{-1} over a large region of Eastern North American, with deposition rates in some areas in excess of 40 kg ha^{-1} yr^{-1} (RMCC, 1986b). Many areas of eastern Northern America have little buffering capacity and so require deposition rates below the rate of 15 kg ha^{-1} yr^{-1} assumed to be sufficiently small at the above-mentioned Stockholm conference. However, acid spikes associated with spring snowmelt and release of acids accumulated over the preceding winter can still have significant effects even when mean annual rates of deposition, if delivered uniformly, would not cause damage.

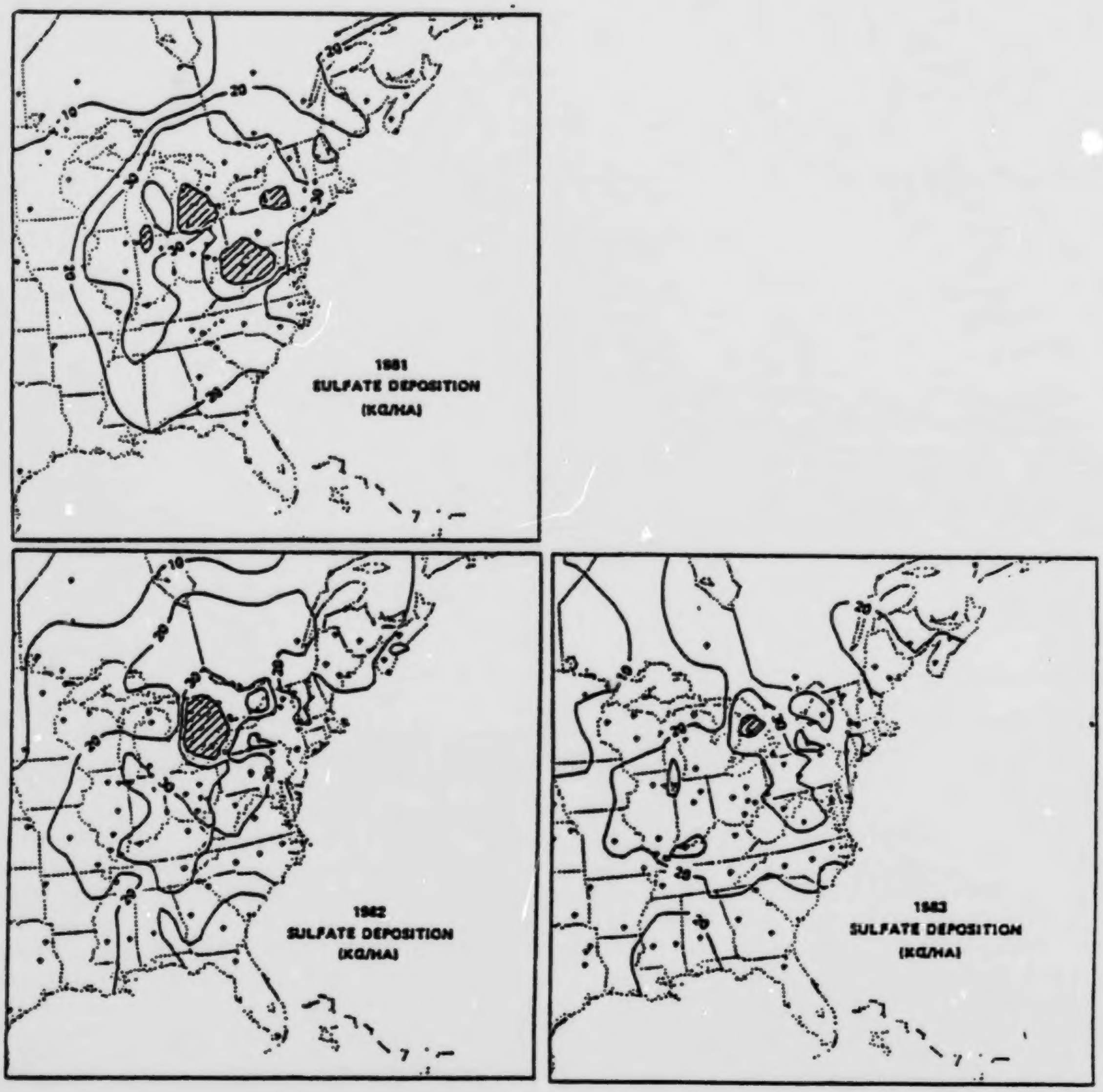

1981
SULFATE DEPOSITION
(KG/HA)
1982
SULFATE DEPOSITION
(KG/HA)
1983
SULFATE DEPOSITION
(KG/HA)

Figure 1. Annual sulfate deposition (Kg ha^{-1} yr^{-1}) in eastern North America for the years 1981, 1982, and 1983 (from RMCC, 1986).

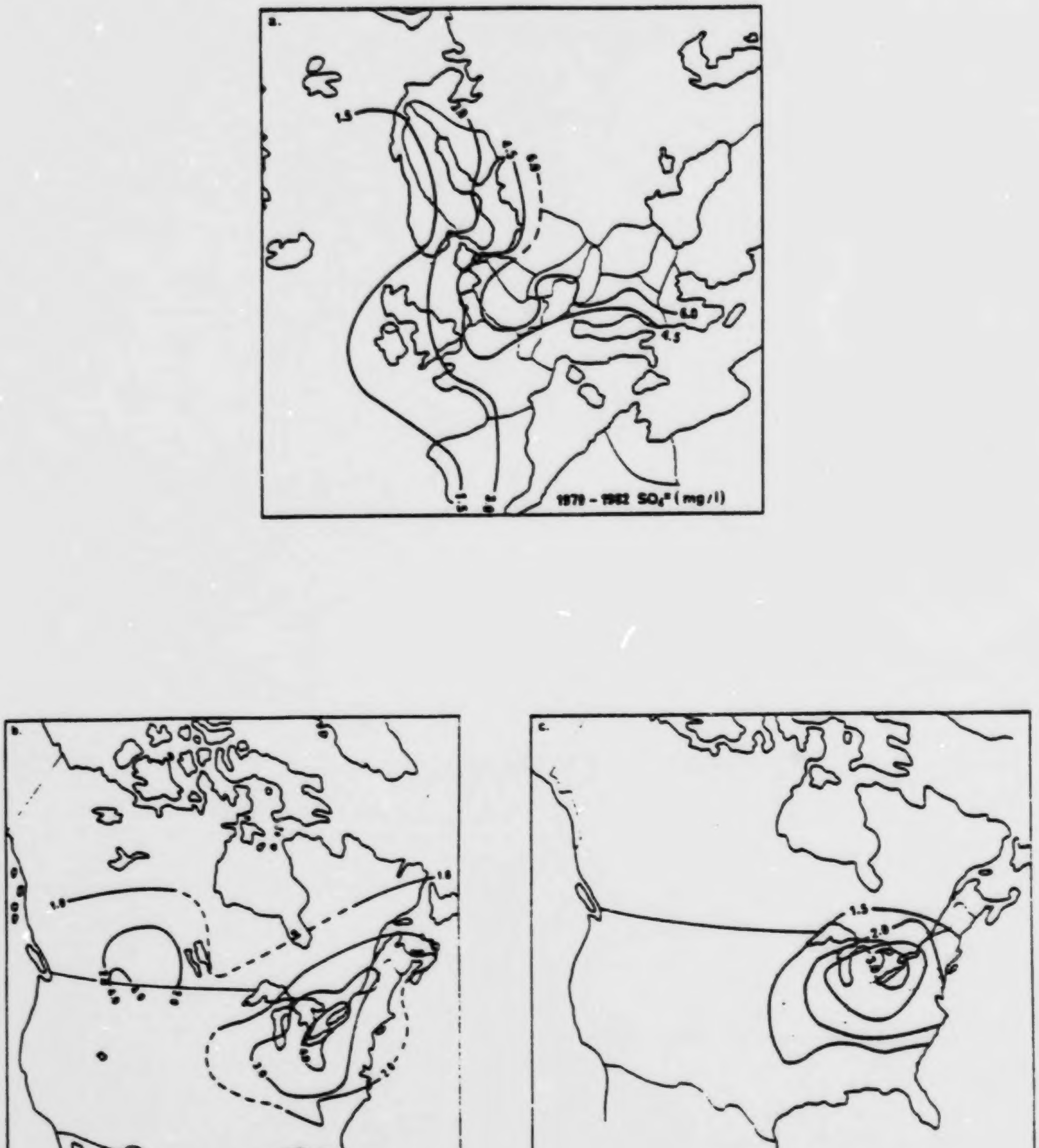

a.
1.5
3.0
4.5
6.0
1979 - 1982 SO₄= (mg/l)
b.
1.5
2.0
1980 SO₄= (mg/l)
c.
1.5
2.0
1983 SO₄= (mg/l)

Figure 2. Comparison of precipitation sulfate levels in Europe (a) and North America (b and c) (from RMCC, 1986).

Table 6. Percentage contribution of different sources to emission of sulphur dioxide and nitrogen oxides in Canada and the USA in 1980 (RMCC, 1986a)

Sulphur dioxide	Canada	USA
Thermal Power Generation	16.5	63.8
Transportation	2.9	3.3
Res\Comm\Ind Fuel Combustion	13.6	17.0
Non-Ferrous	44.9	4.4
Other Industrial Processes	22.1	11.1
Total absolute emission (tons):	4.6×10^6	24×10^6

Nitrogen Oxides	Canada	USA
Thermal Power Generation	14.9	34.2
Transportation	61.8	38.4
Res\Comm\Ind Fuel Combustion	19.3	21.9
Other	4.0	5.5
Total absolute emission (tons):	1.7×10^6	21×10^6

Table 7, taken from Wetstone and Rosencranz (1983), lists some of the options available for reducing SO_2 emissions from coal and oil, and indicates their advantages and disadvantages. Among the options for coal are coal cleaning prior to combustion, fluidized bed combustion (a new combustion method under development), and removal of sulphur from flue gases. A short term option is to switch to low-sulphur coal as long as supplies last, while on a time scale of several decades it is possible to shift to other energy sources for electricity. Removal of flue gases on a large scale would have significant environmental impact; for Britain alone 4 million tons of calcium carbonate would have to be excavated each year and 7.5 million tons of wet calcium sulphate disposed of (Nature, 16 August 1984, pg. 535). Removal of sulphur during fluidized bed combustion would also lead to disposal problems.

Current Canadian regulations call for a reduction by about 50 % in SO_2 emissions by 1994 compared to 1980 emissions (Lewis and Davis, 1986). Reduction of SO_2 emissions from the United States will not be as easy because of the greater importance of

Table 7. SO_2 emission control technologies (source: Wetstone and Rosencranz, 1983).

Technology	Current Status of Development	Removal Capability	Advantages	Disadvantages
CLEANER FUELS				
Low Sulfur Coal	Commercially demonstrated		Abundant reserves in North America Simple emission reduction method	In U.S., could reduce mine employment in eastern coal regions. It is costly to transport western coal to east and Midwest
Coal Cleaning • Physical coal cleaning—"washing"	Commercially demonstrated	Pyritic S removal: 30–over 40% from high sulfur coals 10–20% from low sulfur coals	Produces cleaner fuel with higher Btu content, less variable sulfur content and reduced ash content Physical coal cleaning can provide moderate pollution control gains for total costs substantially lower than FGD costs	Generates large quantities of high sulfur refuse Waste disposal problem due to possible groundwater contamination Loss of about 10% of the coal energy content in the cleaning process Physical coal cleaning is generally not a cost-effective means of reducing emissions from low sulfur coals Chemical coal cleaning has high processing costs
• Chemical coal cleaning	Under development ([illegible] may be commercially demonstrated by late 1980s)	Total S removal: 70–90%		
Coal Liquefaction	Under development (commercially demonstrated by 1990s)	S removal: Up to 100%	Coal liquefaction produces variety of cleaner liquid fuels, and is easier to transport and use than solid fuel SRC is effective on wide variety of coals	Potential to produce toxic by-products
• Solvent Refined Coal (SRC)	Under development	S removal: Almost all pyritic sulfur and 60–75% organic sulfur		
Coal Gasification	Commercially demonstrated in Europe (commercially demonstrated in U.S. by 1990s)	S removal: Greater than 90%	Produces variety of cleaner gases Can be used in combined cycle power power plants	High developmental costs Potential for toxic by-products
Underground Coal Gasification	Under development in U.S.		Produces variety of cleaner gases Minimizes health and safety problems, requires less water and has fewer solid waste problems than convention coal mining	Subsidence problems Potential groundwater contamination Underground mine fires
Low Sulfur Oil	Commercially demonstrated		North Sea oil reserves are low sulfur Increased use of low sulfur oils could potentially reduce Western Europe's annual SO_2 emissions	On a global scale, supplies of low sulfur crude are considerably more limited than supplies of high sulfur crude Many boilers are not able to burn low sulfur oil
Oil Desulfurization • Indirect	Commercially demonstrated	S removal: 30–42%	Increased indirect hydrodesulfurization in Western Europe could reduce region's SO_2 emissions	High costs associated with requirement for large amounts of hydrogen gas
• Direct	Under development (commercially demonstrated by late 1980s)	S removal: Up to 90%	Major means of producing less than 1% fuel oil from high sulfur crudes	High investment and operating costs More difficult technique than indirect desulfurization
Fuel Denitrogenation	Early developmental stages			Carbon deposition on catalyst decreases efficiency High costs associated with requirement for large amounts of hydrogen gas
PROCESS CHANGES				
Staged Combustion	Commercially demonstrated	NO_x emission reduction: 50% for retrofit onto coal-fired plant 60–80% retrofit onto oil-fired plant	Can be retrofitted on some boilers Most economical on new plants	Corrosion of equipment High maintenance requirements
Limestone Injection Multistage Burning (LIMB)	Under development	SO_2 emission reduction: Up to 70% NO_x emission reduction: Up to 70%	Can be retrofitted onto coal-fired plants Can reduce both SO_2 and NO_x emissions	
Fluidized Bed Combustion (FBC) • Atmospheric FBC	Under development (commercially demonstrated by mid-1980s)	SO_2 emission reduction: Over 90%	Can reduce both SO_2 and NO_x emissions FBC wastes may be regenerable into useful products Pressurized FBC operates at higher efficiencies, reduces more SO_2 and NO_x emissions and uses less limestone than atmospheric FBC Pressurized FBC can be used in combined cycle plant	
• Pressurized FBC	(commercially demonstrated after 1995)			
POST-COMBUSTION TECHNOLOGIES				
Flue Gas Desulfurization (FGD) • Wet FGD	Commercially demonstrated (most widely used FGD method)	SO_2 emission reduction: 90%–95%	Can be retrofitted if room available at facility Sludge can be treated for easier handling and potential marketing Some wet FGD systems produce salable products	Generates large quantities of sludge which creates disposal problems Operating problems associated with scaling and plugging, and erosion and corrosion of metal surfaces
• Dry FGD	Commercially demonstrated	SO_2 emission reduction: 70–90%	Can be retrofitted if room available at facility Produces dry waste product Fewer scaling and plugging problems and lower costs than wet FGD systems Consumes less water than wet FGD systems	Only effective with low sulfur coals
• Electron beam	Under development	SO_2 emission reduction: Greater than 95% NO_x removal: 85%	Produces marketable byproducts Can reduce both SO_2 and NO_x emissions	
Flue Gas Treatment • Selective Catalytic Reduction (SCR)	Commercially demonstrated in Japan (under development in U.S.)	NO_x removal: 80%	Can be retrofitted Produces no solid waste	Waste disposal problem with spent catalysts

coal-fired generating plants to total SO_2 emissions in the United States, and regulations to reduce SO_2 emissions have yet to be formulated. Whatever reductions are eventually implemented will be costly. For the most sensitive areas, a 50 % reduction in emissions from both Canada and the United States will not be sufficient, and even for less sensitive areas, a 50 % reduction may not be sufficient in the long run. In the case of Europe, Sweden reduced SO_2 emissions from 450,000 tons in 1970 to 250,000 tons in 1980, largely as a result of a switch to low sulfur fuels (Wetstone and Rosencranz, 1983). In the early 1980's West Germany announced plans to reduce emissions by one third, and there is growing pressure in Britain to reduce SO_2 emissions by 30 percent by 1990 and by 60 percent by 1995 (Nature, 13 Sept. 1984, pg. 94).

Current levels of acid deposition in China are likely to have major effects in China. Sulfate deposition rates over large regions of China are higher than found in the eastern United States as a result of the widespread use of coal in China, and are a cause of great concern about possible future damage to ecosystems (Galloway et al 1987).

In summary, acid deposition is a very serious environmental problem associated with the use of fossil fuels which is likely to cause major ecosystem damage and could have enormous human and economic costs if not reduced by at least 50 percent within the next decade or two. Although it is technically feasible to make these reductions, and the costs of not doing so are almost certainly greater than the costs of reducing emissions, the available short term (10-20 year) strategies for dealing with acid deposition would be difficult to apply in the long term. Supplies of low sulphur coal are limited, and removal and disposal of sulphur from high sulphur coals would in itself have significant environmental effects. The only viable long term strategy for reducing SO_2 emissions may very well be to phase out the use of sulphur containing fuels altogether, and this will require replacing coal with other energy sources when supplies of low sulphur coal are depleted. With regard to NO_x emissions, automobile emissions and coal combustion are both important sources; the former can be reduced through implementation of tighter automobile emission standards as long as supplies of precious metal catalysts are sufficient. Little attention has been given to reducing NO_x emissions from coal-fired generating plants.

1.3 Greenhouse gases.

1.3.1 Carbon dioxide

Until recently, the major trace greenhouse gas of concern was CO_2, a concern motivated by the currently observed rate of increase of atmospheric concentration of this gas, of projections for its doubling near the middle of the next century, and of model calculations of significant climatic impacts associated with even a doubling of CO_2. This is still the single most important trace gas from a climatic point of view, but now a number of other trace gases, dependent at least in part on fossil fuel use, have emerged whose cumulative climatic impact may be 0.2 to 2.2 that of CO_2 alone. This section focuses on CO_2, while other trace gases are discussed later.

An assessment of the possible future impacts of increases in CO_2 on human societies and natural ecosystems involves the following steps: (1) global econometric modelling to develop CO_2 emission scenarios, taking into account projections of population growth, energy supply and costs, per capita energy consumption, efficiency of energy generation and end use, and the mix of fuels used; (2) carbon cycle modelling to determine how much of the emitted CO_2 remains in the atmosphere; (3) climate modelling to determine the climatic impact of a given CO_2 increase, both in equilibrium and during the transient; and (4) computation of physical impacts on natural ecosystems, agriculture, energy supply and demand, and sea level.

Past and current atmospheric CO_2 variation

Measurements of the CO_2 content of gas bubbles trapped in polar ice cores indicate that the pre-industrial atmospheric CO_2 concentration, at the beginning of the 19th century, was 260-290 ppmv (parts per million by volume) (Neftel et al 1985; Raynaud and Barnola, 1985). Direct measurement of the atmospheric CO_2 concentration began in 1958 at Mauna Loa Observatory, Hawaii, at which time the CO_2 concentration was 315 ppmv. The observed CO_2 concentration CO_2 from 1958 to 1984 is shown in Figure 3, from which it can be seen that the CO_2 concentration has increased by 30 ppmv (almost 10 %) in 26 years. A global network of CO_2 monitoring stations established since 1958 confirms that the CO_2 increase is worldwide in scope (Gammon et al, 1985), which is to be expected since CO_2 is well mixed within the atmosphere. The increase since the beginning of the industrial revolution is 55-85 ppmv, or about 20 to 30 %.

Past and current CO_2 emissions

Figure 4 shows the estimated emission of carbon into the atmosphere from the extraction and use of fossil fuels between 1950 and 1982 as estimated by Rotty and Masters (1985). Marland et al (1985) estimated a total emission of CO_2 from burning of fossil fuels in 1980 of 5.3×10^{15} gm C; the breakdown of this

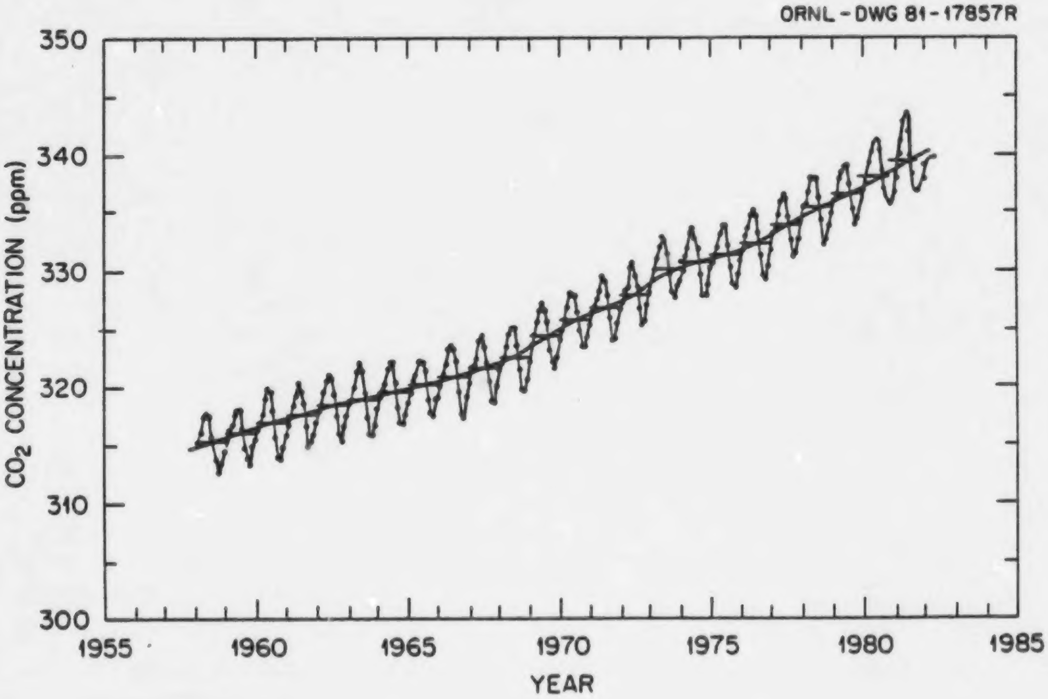


Figure 3. Atmospheric CO_2 concentration as measured at Mauna Loa.

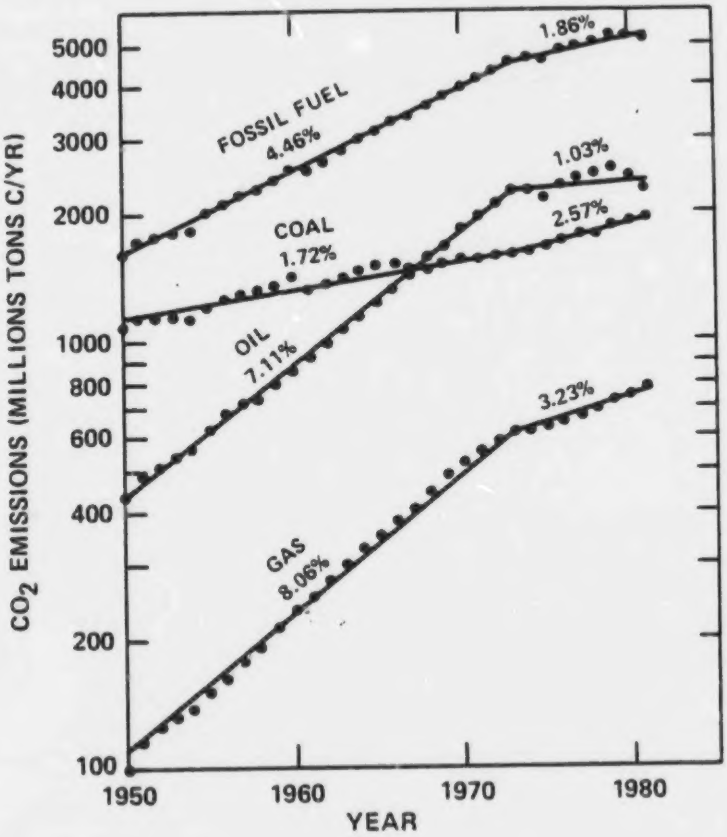


Figure 4. CO_2 emissions from fossil fuel combustion since 1950 as estimated by Rotty and Masters (1985).

Table 8. 1982 CO_2 emissions for the 5 largest producing areas as given by Jovanovich and Rotty (1986), and 1980 CO_2 emissions by source or activity as estimated by Marland et al (1985).

Region	1982 emission (10^6 tons C)
USA	1135.3
USSR	900.9
W. Europe	771.1
China	413.1
Japan	226.4

Source	1980 emission (10^6 tons C)
Solid fuels	1933
Liquid fuels	2210
Gaseous fuels	720
Gas flaring	102
International bunkers	130
Cement manufacture	121
Nonfuel petroleum liquids oxidized	69
Total	5284

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and another estimate of current emission by fuel type and by region is given in Table 8. By comparison, the amount of carbon in the atmosphere as CO_2 is about 720 x 10^{15} gm (Solomon et al 1985). If fossil fuel emissions were the only anthropogenic source of CO_2, then about 58 % of the CO_2 released into the atmosphere from fossil fuels since 1958 has remained in the atmosphere based on the estimated cumulative CO_2 release and the observed atmospheric increase (Rotty and Masters, 1985). This fraction is referred to as the airborne fraction. The cumulative fossil fuel CO_2 emission to 1975 is estimated to be 135 x 10^{15} gm C (Stuiver et al 1984).

There is considerable uncertainty as to the present rate of emission of CO_2 from deforestation and land use changes (referred to as the "biospheric source") or the cumulative release from these activities. Based on $^{13}C/^{12}C$ data from tree rings, Stuiver et al (1984) estimated the cumulative biospheric source from 1600 to 1975 to be 150 +100 x 10^{15} gm C, while Siegenthaler and Oeschger (1987) estimated on the basis of data from polar ice cores that the cumulative biospheric source to 1980 is 90-150 x 10^{15} gm C but that the mean emission during the past 30 years was only 0-0.9 x 10^{15} gm C yr^{-1}. This latter estimate is in agreement with Elliot et al (1985), who estimated the biospheric source to be less than 0.5 x 10^{15} gm C per year based on a comparison of fossil fuel emissions and atmospheric CO_2 concentration since 1958. Estimates of the current biospheric source based on observed land use changes, however, tend to be larger than estimates based on other methods. Houghton et al (1987) estimated the global biospheric source for 1980 to be 1.8 +0.9 x 10^{15} gm C. Land use based estimates and other estimates of the current size of the biospheric source could be reconciled if regrowth of midlatitude forests is a larger CO_2 sink than generally assumed. Tropical deforestation is a net source of CO_2 for the atmosphere today, but regrowth of midlatitude forests may be a sink of perhaps 1 x 10^{15} gm C per year (Kerr, 1980). To sum up, cumulative release of CO_2 into the atmosphere from fossil fuel combustion and from land use changes appear to be comparable, most of the biospheric emission seems to have occurred before 1900, and the current net biospheric source appears to be small compared to be current fossil fuel source. There is, nevertheless, considerable uncertainty concerning the current biospheric emission rate.

The net biospheric emission rate has implications for the airborne fraction and future CO_2 levels resulting from fossil fuel use, since the larger the current biospheric emission the smaller the empirically determined airborne fraction. Oeschger and Heimann (1983) estimated that the airborne fraction since 1958 is between 0.38 to 0.72.

Upper limit to atmospheric CO_2 increase

Table 9 shows the sizes of the ultimately recoverable resources of oil and natural gas, and of the physical amount of coal present in various geographical regions as estimated by Rotty and Marland (1980). The ultimately recoverable resource is that portion of the total resource believed or known to exist which is estimated to be technically recoverable without regard to the cost of recovering it, and should be distinguished from reserves, which is that portion of the resource which could be recovered using present technology under current economic conditions. The carbon content of the ultimately recoverable resources indicates the potential for emissions of CO_2 to the

Table 9. Global distribution of ultimately recoverable conventional crude oil and natural gas, and of coal resources as estimated by Rotty and Marland (1980). 1 tce = 1 ton coal equivalent = 10^3 kg coal with a heating value of 7000 cal/gm, for a total heating value of 20.31 x 10^9 J.

Region	Oil (10^9 tons)	Gas (10^{12} m^3)	Coal (10^9 tce)
USSR	59.4	88.5	4860
E. Europe			171
China		10.4	1438
USA	28.5	50.7	2685
Canada			
Middle East	109.1	96.2	0
N. Africa		1.0	172
Sub Saharan Africa	11.3	0.4	
W. Europe	11.2	12.2	420
Latin Amer	22.9	11.6	32
Japan, Aust, New Zealand	15.1	7.1	0
Deep Offshore	34.0	0.0	0
Other	0.0	5.2	76
Total	291.5	273.4	10126

Table 10. Carbon content (10^{15} gm) of global fossil fuel reserves and resources as estimated by Rotty and Masters (1985) for coal, oil, and natural gas, and by Rotty and Marland (1980) for shale oil and tar sands, in comparison with the atmospheric carbon content as CO_2. Also given is the current atmospheric CO_2 concentration and the atmospheric CO_2 increase (ppmv) that would occur if the total recoverable resources were burnt with an airborne fraction of 0.5.

	Demonstrated	Total recoverable resources	
Fuel	Reserves	C content	CO_2 increase
Petroleum	87	126-257	30-60
Natural gas	33-38	99-137	23-32
Coal	485	3440-3840	808-902
Shale Oil[1]		173-9530	41-2239
Tar sands[2]		75-200	18-470
Total		3913-13964	920-3281
Atmosphere		720	345

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[1] Assumes global shale oil resources of 445 x 10^9 tons oil and 50 % recoverable for the lower estimate, and 49,624 x 10^9 tons oil with 25 % recoverable for the upper estimate.

[2] Assumes a global tar sand resource of 327 x 10^9 tons oil with 30 % recoverable for the lower estimate, and 80 % recoverable for the upper estimate.

Table 11. CO_2 emission factors and CO_2 released in the production and combustion of various fuels as estimated by Rotty and Masters (1985) (Reference 1) and by Marland (1983) (Reference 2). 1 MJ = 10^6 J; tce = ton coal equivalent.

	Emission factor	CO_2 released in production and combustion	
Fuel	Ref. 1	Ref. 1	Ref. 2
Coal at minehead	0.693 ton C/tce	23.8 g C/MJ	24.7 g C/MJ
Crude petroleum	0.769 ton C/ton	19.2 g C/MJ	---
Refined petroleum	---	---	22.3 g C/MJ
Natural gas	0.524×10^{-3} ton C m^{-3}	13.7 g C/MJ	16.4 g C/MJ
Shale oil	---	27.9 g C/MJ	---
Gasification of coal	---	---	37-46 g C/MJ
Liquefaction of coal	---	---	31-42 g C/MJ

atmosphere. The carbon content of fossil fuel reserves and total recoverable resources as estimated by Rotty and Masters (1985) for coal, oil, and natural gas, and by Rotty and Marland (1980) for shale oil and tar sands, is given in Table 10. The total carbon content of the estimated ultimately recoverable fossil fuel resources is 3913 to 13964 x 10^{15} gm. This is about 6 to 20 times the amount of carbon currently in the atmosphere as CO_2, which is 720 x 10^{15} gm. Also shown in Table 10 is the increase in atmospheric CO_2 concentration which would occur if the estimated ultimately recoverable resources were burnt, assuming a 50 % airborne fraction. It is seen that simply burning all the remaining recoverable conventional liquid fuels would increase atmospheric CO_2 by only 15 to 26 % above its current concentration of 345 ppmv. Burning the vast amount of recoverable solid fuels, on the other hand, could increase atmospheric CO_2 by a factor of 3 to 11 above the mid-nineteenth century concentration of 290 ppmv.

Table 11 shows emission factors in terms of mass of CO_2 emitted per mass or volume of fossil fuel, as well as CO_2 emitted per unit intrinsic energy for various fossil fuels. More detailed

Table 12. Potential contribution (10^{15} gm C) to atmospheric CO_2 of selected countries and regions based on estimated ultimately recoverable resources without regard to price. ME/NA = Middle East and North Africa.

Region	Coal	Oil	Natural Gas	Tar Sands	Oil Shales	Total
USSR	1701	45.7	41	---	---	1750
China	503		5.5	---	---	550
USA	727	18.6	17.8	---	107	871
Canada	213	3.3	5.0	3.1-78	---	224-300
W. Eur.	147	8.6	6.6	---	---	162
ME/NA	---	84	5.0	---	---	89

comparisons of the various fossil fuel sources must take into account the fraction of deliverable end-use energy and end-use efficiencies, an example of which may be found in Marland (1983). Since coal is deficient in hydrogen compared to conventional liquid and gas fuels, production of synthetic liquids and gases from coal requires either removal of excess carbon or addition of extra hydrogen; the range of CO_2 emission rates given in Table 11 for gasification and liquefaction of coal are for different processes involving carbon removal. If synthetic liquid fuels produced from coal replace conventional liquid fuels as they are depleted and carbon removal rather than hydrogen addition is used, than the rate of CO_2 increase will be larger for a given total primary energy consumption than if conventional liquid fuels were still available. Thus, both the total atmospheric CO_2 input and the rate of input depend critically on whether or not coal and, to a lessor extent, shale oil and tar sands are used to manufacture synthetic liquid fuels.

Table 12 shows the potential contribution to atmospheric CO_2 for selected countries and regions based on the estimates of ultimately recoverable resources given in Table 9, except for Canada, were estimates of ultimately recoverable resources given by Robinson (1987a) are used. To convert to ppmv, these numbers can be multiplied by 0.47 times an assumed airborne fraction of 0.5. Very approximate contributions of individual regions to the potential atmospheric CO_2 increase are as follows: USSR, 411 ppmv; USA, 205 ppmv; China, 129 ppmv; Canada, 53-71 ppmv; Western

Europe, 38 ppmv; Middle East and North Africa, 21 ppmv. Thus, only four countries account for most of the potential increase in atmospheric CO_2, which may make it easier to reach international agreement on limiting the CO_2 increase. Bowman and du Plessis (1986) estimated the recoverable coal in Canada to be about three times larger than estimated by Robinson (1987a), corresponding to a carbon content of 610 x 10^{15} gm. This higher coal estimate gives a potential CO_2 increase from Canada alone of about 155-175 ppmv.

CO_2 emission scenarios

Scenarios of future CO_2 emissions are dependent on the assumed future global energy use and the mix of fuels used, and differ dramatically as illustrated in Figure 5, which shows projected CO_2 emissions for various scenarios made in the 1970's and early 1980's as compiled by Perry (1982). One scenario has annual CO_2 emissions increasing from 5 x 10^{15} gm C yr^{-1} at present to 90 x 10^{15} gm C yr^{-1} in the middle of the next century. Early studies assumed growth rates for CO_2 emissions of around 4.5 % per year, based on an extrapolation of past trends. By 1982, Perry (1982) estimated that the CO_2 emission growth rate would be less than 3 percent per year and could very well be as little as 1.5 percent per year.

Two later studies, Nordhaus and Yohe (1983) and Edmonds et al (1986), used probabilistic scenario analysis in which the effect of uncertainties in model variables is estimated, and projected even smaller growth rates of CO_2 emissions. In this approach the probability distribution for various model input parameters is estimated and used to generate a large number of scenarios (1000 for Nordhaus and Yohe, 400 for Edmonds et al (1985), each scenario being the result of input parameters selected from the probability distributions for each individual input parameter. Nordhaus and Yohe (1983) estimated the most likely CO_2 emission growth rate between 1975 and 2100 to be 1.2 % per year, with 90 percent confidence bounds of 0.3 and 2.0 %. Edmonds et al (1986) obtained median growth rates over the next 100 years of 1.0 % when 42 of the 79 model input parameters were assumed to be distributed independently of each other (the "zero-correlation" case), but only 0.6 % if additional correlations between input variables were assumed when generating the scenarios. In the former case 90 % confidence bounds were from a decrease in emissions of 1.4 % per year to an increase of 3.0 %. Plots of carbon emission percentiles based on these results are given in Figure 6. The median CO_2 emission rate for 2075 is 13 x 10^{15} gm C for the zero correlation case, and 8 x 10^{15} gm C for the non-zero correlation case, but the uncertainty is large. Interestingly, recent data of Rotty (1987) indicate that global CO_2 emissions from fossil fuels decreased for four consecutive years between 1979-1983 as result of reduced use of liquid fuels

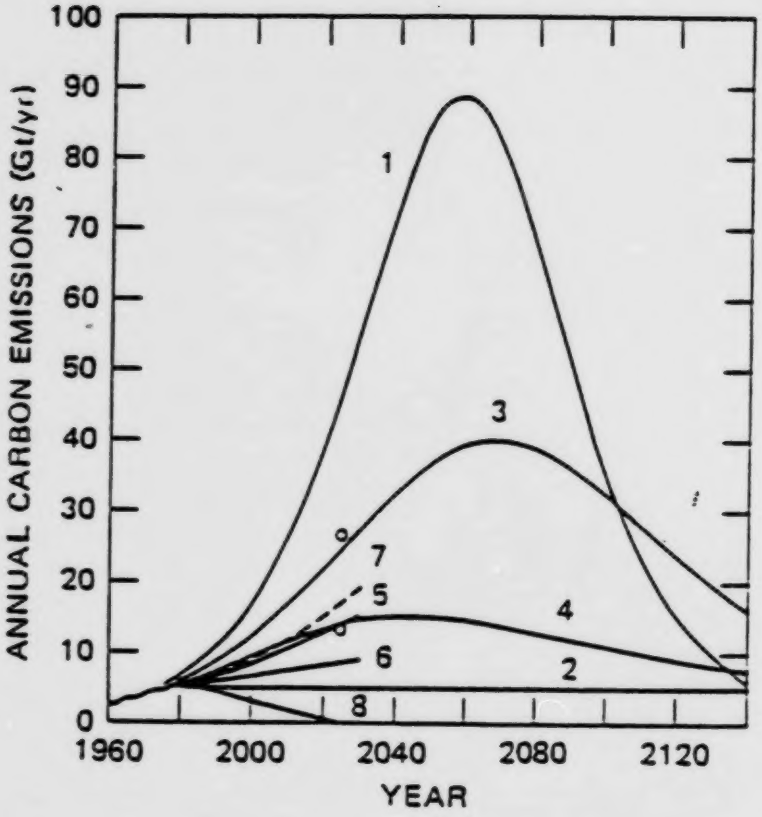


Figure 5. Various projections of future CO_2 emissions as compiled by Perry (1982).

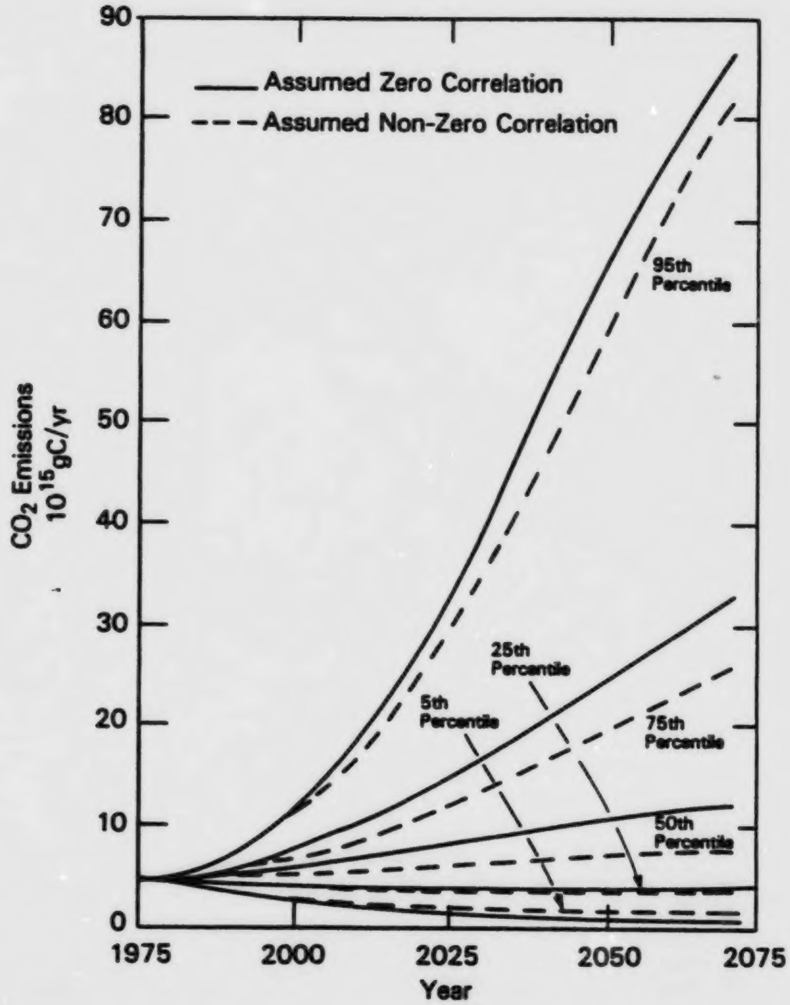


Figure 6. Projected CO_2 emission rates as given by the 95th, 75th, 50th, 25th, and 5th percentiles of the randomly generated scenarios considered by Edmonds et al (1986).

and a very slow increase in the use of gas and solids. Preliminary data for 1984, however, indicate that a resumption in the increase of CO_2 emissions occurred.

Atmospheric CO_2 concentration scenarios

Given a scenario of atmospheric CO_2 emissions, a carbon cycle model is needed to estimate what fraction of the emitted CO_2 remains in the atmosphere during the transient and in equilibrium, and what fraction is transferred to other carbon reservoirs. Table 13 gives the estimated size of the various carbon reservoirs. The atmosphere is in direct contact with the surface mixed layer of the ocean, and the atmospheric and mixed layer CO_2 contents equilibrate on a 1 year time scale (Broecker and Peng, 1982). Increased plant growth in direct response to elevated atmospheric CO_2 would tend to increase the size of the terrestrial biosphere, and would thus serve as a sink for some of the increased atmospheric CO_2. However, the current size of the terrestrial biosphere is only about 1800 x 10^{15} gm C (Table 13), compared to a carbon content of the estimated ultimately recoverable fossil fuel resources of 3900 to 14,000 x 10^{15} gm. Even with deliberate international efforts to increase the size of the terrestrial biosphere by promoting regrowth of forests, the terrestrial biosphere could not serve as a significant sink for fossil fuel CO_2.

The ocean is expected to be the major sink for fossil fuel CO_2, and the oceanic ability to absorb fossil fuel CO_2 determines the airborne fraction - the fraction of CO_2 emitted into the atmosphere which remains in the atmosphere. As previously noted, the empirically estimated airborne fraction since 1958 is 0.38 to 0.72. Dissolution of CO_2 in the ocean consumes carbonate (CO_3^{-}),and the ultimate capacity of the ocean to absorb anthropogenic CO_2 depends on the supply of carbonate. Three steps can be identified in the oceanic uptake of fossil fuel CO_2: (1) dissolution into and equilibration with the oceanic mixed layer, which occurs on a one year time scale; (2) downward mixing into the deep ocean, making available the much larger carbonate supply of the deep ocean, but occurring on a time scale of 100 to several hundred years; and (3) dissolution of $CaCO_3$ sediments on the ocean floor. The third step will not begin until surface water with fossil fuel CO_2 reaches the ocean bottom, and will not affect atmospheric CO_2 until it has again returned to the surface - a circuit which takes on the order of 1000 years. Since only partial neutralization of fossil fuel CO_2 by dissolution of $CaCO_3$ is likely to occur during each circuit, complete equilibration will most likely require on the order of several thousand years. The final equilibrium atmospheric CO_2 increase might be as little as 1/8 to 1/4 the total anthropogenic input, depending on the magnitude of the input (Siegenthaler and Oeschger, 1978). That

Table 13. Estimated carbon content of various carbon reservoirs as conceptualized in carbon cycle models. Source: Rotty (1978), except where other values have been given in the text.

Reservoir	Size (10^{15} gm C)
Atmosphere	720
Terrestrial biosphere	
rapid turnover	160
slow turnover	1600
Ocean water	
surface	580
thermocline	6600
deep	31800
Marine organic matter	
living	1
dead	1650
Reactive sediments	400
Recoverable fossil fuels	4000-14000

is, the equilibrium airborne fraction could be 1/4 to 1/8, with larger values corresponding to larger absolute inputs.

The time scale for increase of CO_2 emissions has been much shorter (35 year doubling time for 2 % growth per year) then the time scale for mixing into the deep ocean (100 to 1000 years), so that much larger transient increases and temporarily large airborne fractions will occur than would occur in equilibrium even in the absence of $CaCO_3$ dissolution. The airborne fraction during the transient thus depends on the rate of CO_2 input, and will be smaller for smaller CO_2 emission rates, as illustrated by Laurmann and Spreiter (1983).

Figure 7 shows four different CO_2 emission scenarios in which an amount of fossil fuel carbon equal to 8.2 times the pre-industrial atmospheric CO_2 content (assumed to be 290 ppmv) is consumed in each case, and Figure 8 shows the atmospheric CO_2 concentration as computed by Keeling and Bacastow (1977) for these scenarios. Atmospheric CO_2 peaks at 7 to 8 times the present concentration between A.D. 2100 and 2200, then gradually declines as a result of gradual mixing of CO_2 into the deep ocean. As previously noted, the equilibrium atmospheric CO_2 concentration might be as little as 1/8 to 1/4 the total input.

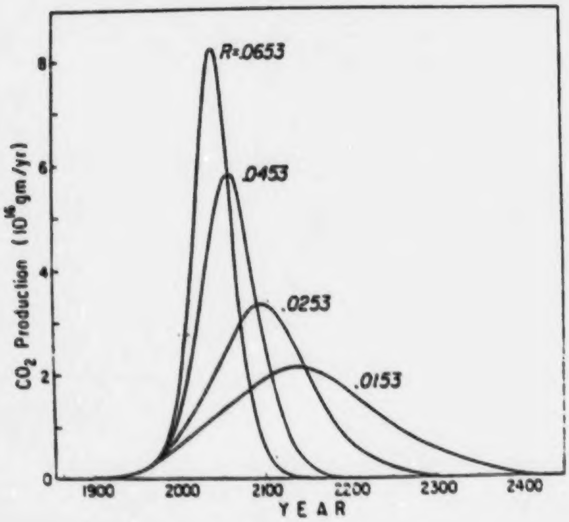


Figure 7. Patterns of CO_2 emission considered by Keeling and Bacastow (1977) in which an amount of carbon equal to 8.2 times the pre-industrial atmospheric CO_2 content is consumed.

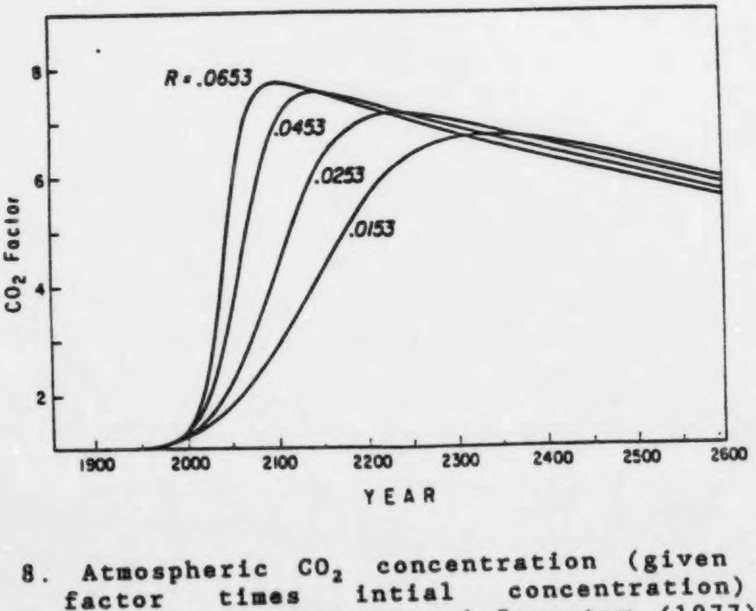


Figure 8. Atmospheric CO_2 concentration (given as a factor times intial concentration) as computed by Keeling and Bacastow (1977) for the four emission scenarios shown in Fig.5.

Since the equilibrium atmospheric CO_2 concentration for smaller total inputs might very well be acceptable whereas the peak concentration probably would not be, it can be seen that the CO_2 problem is largely a problem with the rate at which fossil fuels are being consumed. To avoid peak atmospheric CO_2 concentrations in excess of the equilibrium CO_2 concentration, however, necessitates releasing the fossil fuel CO_2 over a time period comparable to the equilibration time scale for the atmosphere-ocean-sediment system - hence over a period of several 1000 years.

Figures 9 and 10 show the increase in atmospheric CO_2 concentration above an assumed pre-industrial level of 300 ppmv for CO_2 emission growth rates of 3 % per year and 1.53 % per year, respectively, as calculated by Laurmann and Spreiter (1983) for three different carbon cycle models. Doubling of the atmospheric CO_2 concentration occurs by 2040 for the fast growth rate and by 2070 for the slow growth rates; adopting the CO_2 emission growth rates of Edmonds et al (1986) would delay the CO_2 doubling time to near the end of the next century or later.

The above calculations do not take into account the feedback between oceanic temperature and oceanic solubility for CO_2. As the ocean warms in response to an increase of atmospheric CO_2 its solubility for CO_2 will decrease, leading to release of some of the CO_2 already dissolved in the ocean, a further increase of atmospheric CO_2, and further warming. According to Siegenthaler and Oeschger (1978), global mean oceanic warmings of 1.5 and 3.0 °C, which might accompany a CO_2 increase from 290 to 580 ppmv, would increase atmospheric CO_2 by 44 and 87 ppmv, respectively. These increases are 15 and 30 percent of the original CO_2 increase and thus represent a strong positive feedback.

It is also important to note that data on atmospheric CO_2 concentration variations between 30,000 and 40,000 years ago obtained from air bubbles in polar ice cores indicate that atmospheric CO_2 variations of 50-70 ppmv occurred on time scales of a few hundred years or less and were correlated with climatic changes (Stauffer et al 1984). Most of the theories proposed to explain these variations invoke climate-induced changes in the circulation of the upper ocean (Siegenthaler and Wenk, 1984; Broecker and Takahashi, 1984; Southam and Peterson, 1985; Wenk and Siegenthaler, 1985). Baes (1982) and Broecker and Takahashi (1984) suggest that climatic warming following a CO_2 increase would alter oceanic circulation in such a way as to lead to a further increase of atmospheric CO_2. Thus, data on natural atmospheric CO_2 variations, although scientifically intriguing in their own right, serve as a strong warning of the possible sensitivity of the natural carbon cycle to perturbations by Mankind.

Finally, positive feedbacks between climate and the methane

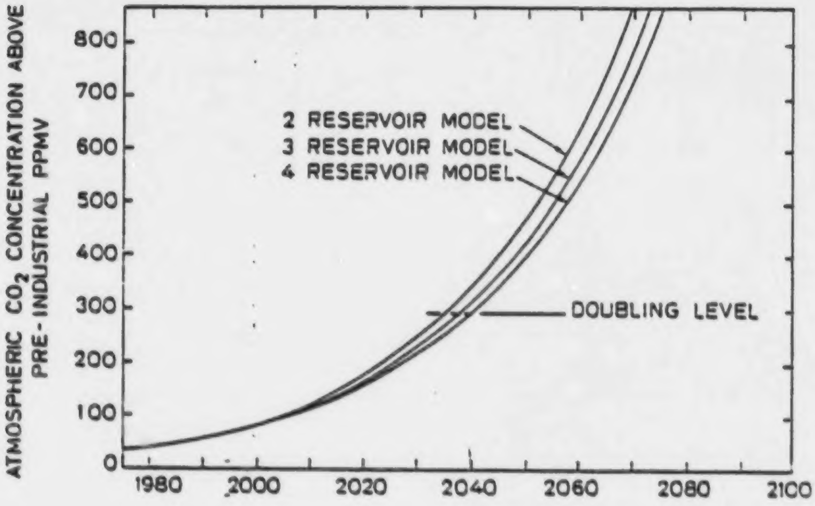


Figure 9. Increase in atmospheric CO_2 as calculated by Laurmann and Spreiter (1983) using three different carbon cycle models with CO_2 emissions increasing by 3 % per year.

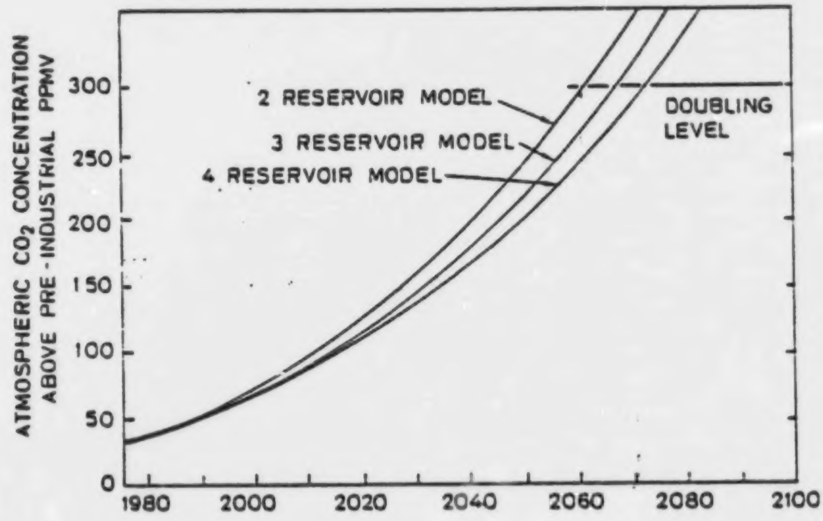


Figure 10. Increase in atmospheric CO_2 as calculated by Laurmann and Spreiter (1983) using three different carbon cycle models with CO_2 emissions increasing by 1.53 % per year.

cycle have also been suggested which would lead to an increase in methane (above direct anthropogenic increases), thereby increasing the overall greenhouse warming (Bell, 1982; Guthrie, 1986). The magnitude of this potential feedback is very uncertain but could be significant.

Climatic impact of a CO_2 increase

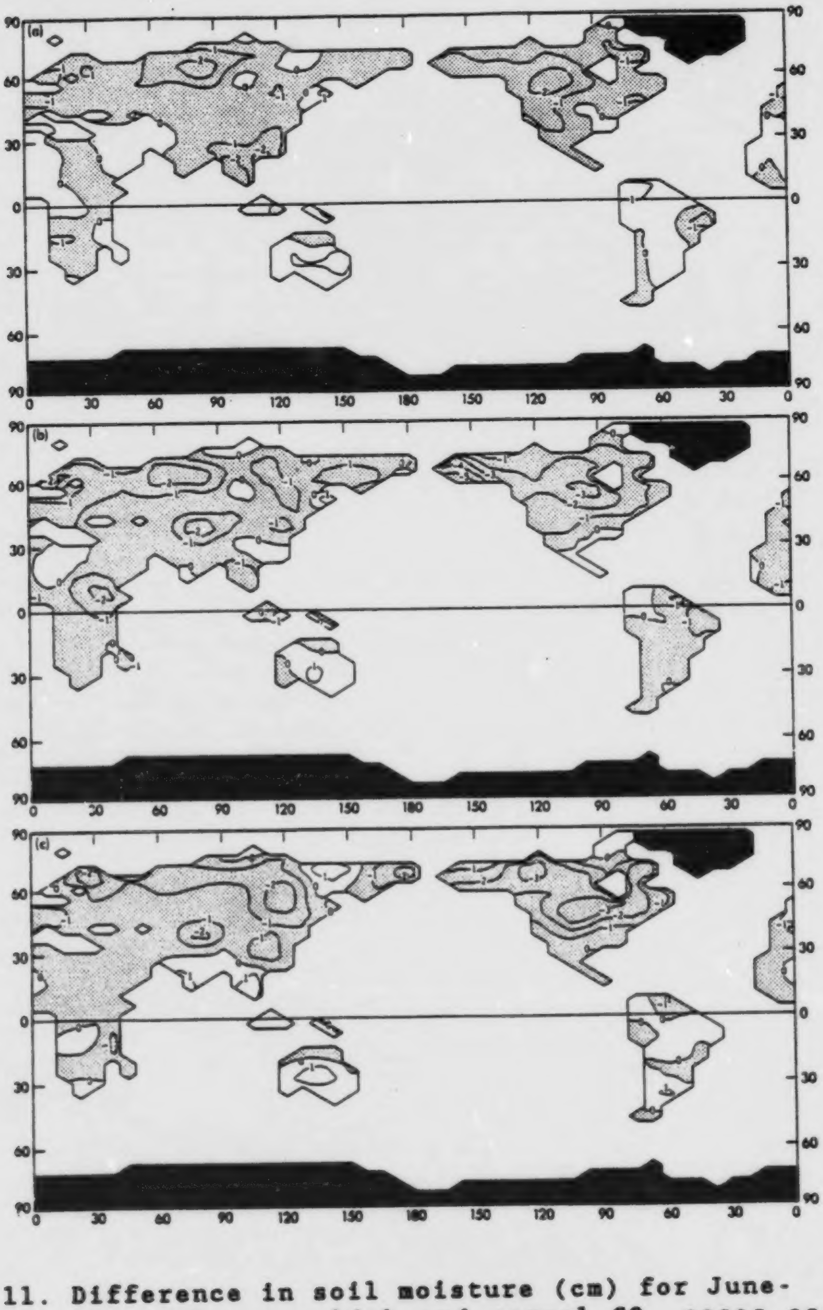
A wide range of climate models have been used to estimate the climatic impact of a CO_2 increase. For a given time-dependent CO_2 increase, there are two climate modelling problems involved: one is to compute the equilibrium climate response for a given CO_2 amount. Because of the presence of the oceans, however, the actual climatic response would lag behind the equilibrium response by one to several decades. This is the problem of the transient response, and is far from settled (Harvey, 1986).

The most sophisticated models used to compute the equilibrium climatic response to a CO_2 increase are three-dimensional atmospheric models which compute horizontal winds and vertical motions, temperature and pressure fields, and precipitation, surface evaporation, and runoff from continents. These models, referred to as General Circulation Models (GCM's), also include solar and infrared radiative processes, and many of the most recent GCM's also predict cloud amounts. The latest results from three different GCM's give global, mean annual equilibrium temperature warmings for a CO_2 doubling of 3.0 - 4.2 °C, with a 2 - 3 times greater warming in polar regions (Schlesinger and Mitchell, 1985). However, the latest GCM studies all make essentially the same assumptions regarding cloud-radiation feedbacks, so their agreement is no guarantee of accuracy. In particular, all the latest GCM's neglect a number of potentially important negative feedback processes between cloud radiative properties and climate which, if included, would likely reduce their response to 2.0 - 3.0 °C (Somerville and Remer, 1984; Charlock and Ramanathan, 1985). On the other hand, the models might also neglect positive feedbacks which, if included, would increase their response. Nevertheless, a 2 - 3 °C globally averaged climatic warming from CO_2 doubling alone, with a 2 - 3 times greater warming in polar regions, is a very significant climatic change! By comparison, the globally averaged temperature difference between glacial and interglacial periods is only about 5 °C. A 2 - 3 °C globally averaged warming would make the climate warmer than at any time during the past 100,000 years.

In addition to changes in temperature, GCM's also predict significant changes in the latitudinal and seasonal distribution of precipitation and in soil moisture during the growing season. Model studies using various versions of the Geophysical Fluid Dynamics Laboratory (GFDL) GCM of Princeton University have consistently given reduced summer soil moisture and increased drought over extensive midcontinental regions of North America and Eurasia (Manabe et al 1981; Manabe and Wetherald, 1987). The change in summer soil moisture for a CO_2 doubling as predicted by the latest GFDL study is shown in Figure 11 in absolute terms and in Figure 12 as a percentage. Comparison of temperature and rainfall patterns during the five warmest years in the period 1925-1974 with the five coldest in this period also suggests that climatic warming would be associated with reduced precipitation in the central USA and over much of Europe and Russia (Wigley et al 1980). Summer soil moisture changes for a CO_2 doubling as predicted by the National Center for Atmospheric Research (NCAR) GCM (washington and Meehl, 1984) are shown in Figure 13. The NCAR model gives a smaller reduction of summer soil moisture in North America, Europe, and Russia for a CO_2 doubling than given by the GFDL GCM, but gives larger (and significant) reductions of soil moisture in Southeast Asia and India (Washington and Meehl, 1984).

Reconstructed moisture patterns during a period 5000-8000 years ago, when the global mean climate was about 1.0-1.5 °C warmer than now, indicate that central North American was drier than now but that Eurasia (including Southeast Asia) was moister than now (Kellog, 1979) - in disagreement with GCM results for a CO_2 doubling. However, simulations with the NCAR GCM using the boundary conditions and seasonal distribution of incoming solar radiation (insolation) for that time indicate that changes in the seasonal distribution of insolation were largely responsible for the moisture patterns of that time (Kutzbach and Guetter, 1986). Indeed, the ability of the NCAR GCM to simulate the moisture patterns of 5000-8000 years ago (and earlier) is at least a partial confirmation of the model's large scale moisture response to large scale changes in heating and temperatures, and lends credibility to the changes in large scale moisture patterns predicted by GCM's for a CO_2 doubling.

It is frequently stated in the climate and carbon cycle modelling literature that the direct radiative greenhouse effect of CO_2 and the resultant climatic response (assuming the climatic response to be linear) scales with the logarithm of the fractional CO_2 increase. Thus, fourfold and eightfold CO_2 increases lead to climatic responses 2 and 3 times that for a CO_2 doubling, respectively. This statement, however, neglects secondary CO_2 absorption bands which are not important for a CO_2 doubling but are important for larger CO_2 increases, and whose greenhouse effect increases linearly with CO_2 amount beyond even 8 times present CO_2. The actual climate response would be about 30 % larger for 4 times present CO_2 and 45 % larger for 8 times present CO_2 if one takes into account these absorption bands (Augustsson and Ramanathan, 1977). The important point here is that the greenhouse effect of CO_2 does not saturate as CO_2 increases beyond twice its present amount, so that continued CO_2 increases beyond a doubling will lead to almost proportionately


(a)
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120
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30
0
-1
-2
0

Figure 11. Difference in soil moisture (cm) for June- July-August between high and normal CO_2 cases as obtained by Manabe and Wetherald (1987) with the GFDL climate model for (a) 2 x present CO_2 as the high CO_2 case with fixed cloudiness, (b) 4 x present CO_2 with fixed cloudiness, and (c) 2 x present CO with model-predicted cloudiness. Stippled areas indicate a decrease in soil moisture.

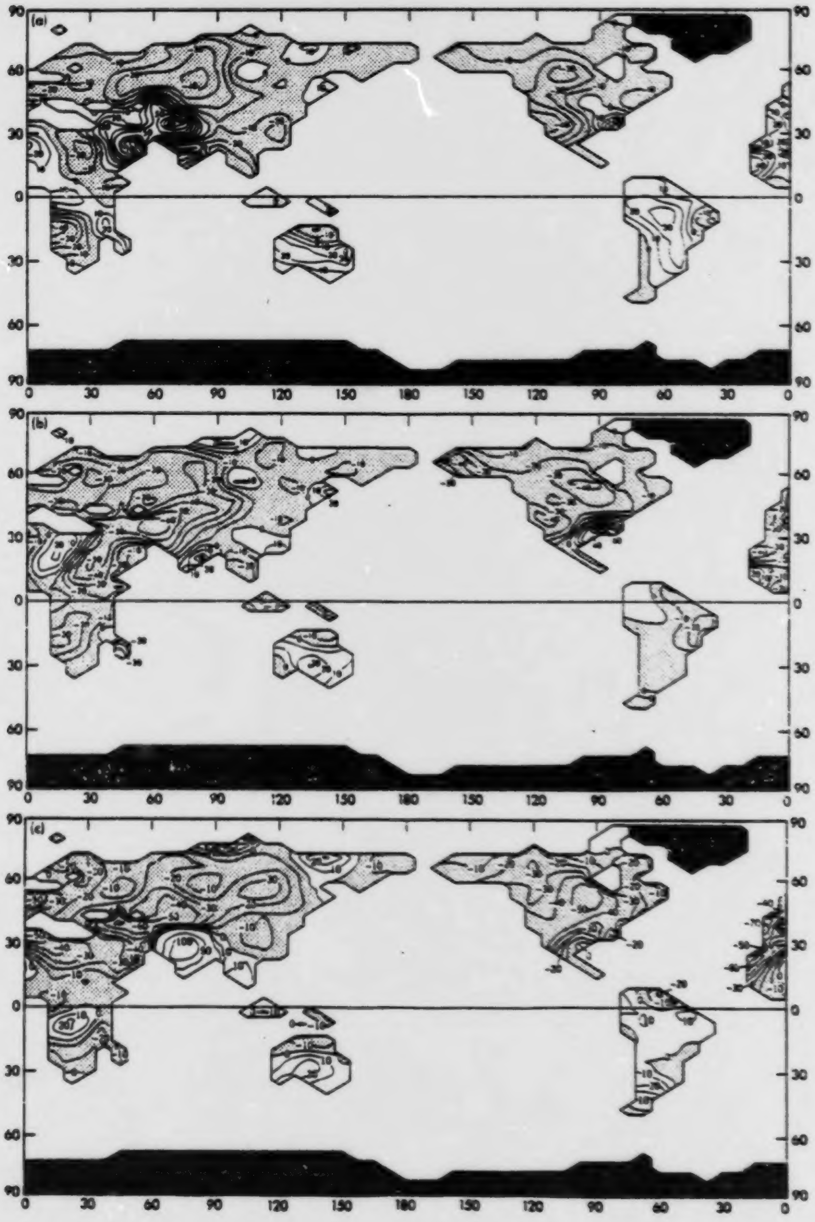
(a)
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Figure 12. Same as Figure 11, but expressed as a percentage.

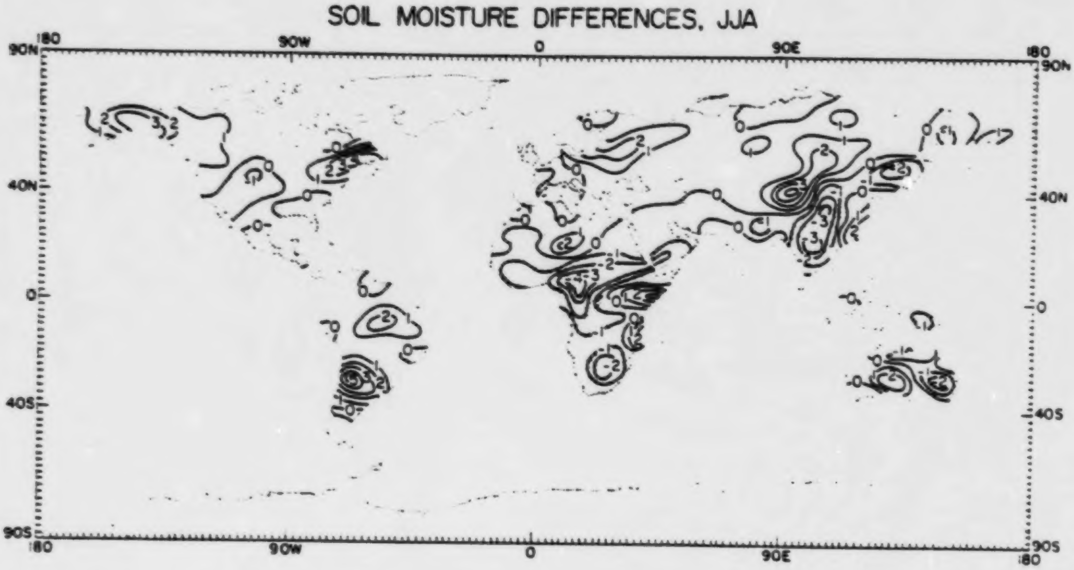
SOIL MOISTURE DIFFERENCES, JJA
180
90W
0
90E
180
90N
40N
0
40S
90S

Figure 13. Difference in soil moisture (cm) for June-July-August between 2 x present and normal CO_2 cases as obtained by Washington and Meehl (1984) with the NCAR model.

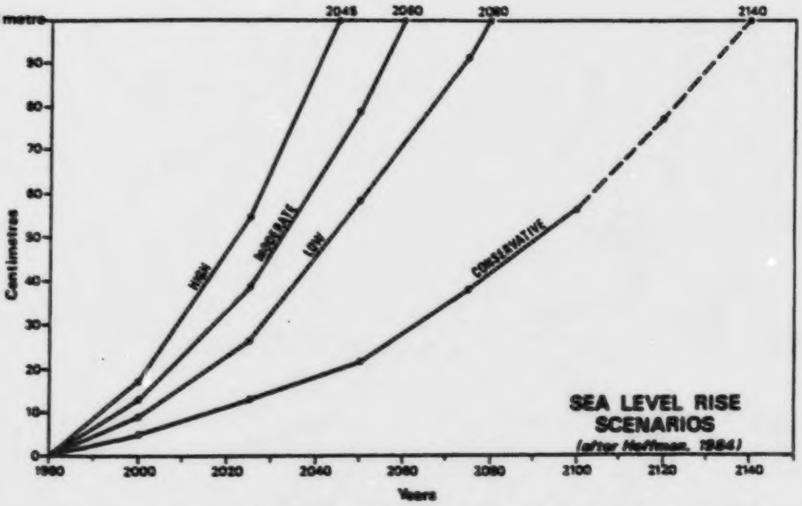

Figure 14. Scenarios for sea level rise, from Hoffman (1984).

larger climatic responses.

To sum up, the most likely equilibrium, global mean temperature response to a CO_2 doubling is a warming of 2-3 °C, with a 2-3 times greater warming in polar regions. GCM results give reductions of summer soil moisture in midlatitudes, although there are significant disagreements between the models as to the magnitudes (and sometimes the sign) of soil moisture changes in specific regions. Use of warm years in the historical past as analogues for a CO_2-induced warming supports the expectation of reduced soil moisture in midlatitudes associated with a climatic warming. If CO_2 increases beyond a doubling then further substantial climatic changes can be expected. A prudent global society would therefore immediately begin planning for the phasing out of fossil fuels at a rate such that the curve representing atmospheric CO_2 would asymptote to the doubling level or less.

Impacts of climatic change associated with CO_2 doubling

The impact on agriculture of CO_2-induced climatic change depends on the detailed seasonal and regional distribution of temperature and precipitation changes. Even if current models are reliable for predicting continental scale and gross seasonal changes, they are not yet reliable enough for predicting climatic changes at the spatial and temporal scales needed to reliably predict agricultural impacts; hence, only rough generalizations have been possible so far (i.e.: Pulwarty and Cohen, 1984). A number of adaptations to reduced soil moisture are possible if the changes are not too large, including switching to more drought resistent crops, developing and/or switching to more drought resistent varieties, improving existing irrigation efficiencies, extending the area under irrigation if surplus runoff is still available under changed climatic conditions, and improving the storage of any surplus water. In addition to the effects of CO_2 on agriculture through induced changes in climate, there are a number of potentially beneficial direct physiological effects of elevated CO_2 levels on plants such as increased photosynthesis and water use efficiency (Lemon, 1983). In the case of Canada and other high latitude countries, the direct effects of CO_2 on plants coupled with longer growing seasons would favour agriculture, although in the case of Canada soil conditions would limit the extent to which agriculture could shift northward. At the same time, soil moisture levels could decrease in some areas and the incidence of droughts could increase. Given modest increases in water use efficiency, selective breeding in anticipation of climatic changes, and crop substitution, it is possible that the net effect of a CO_2 doubling on Canadian agriculture would be positive (Stewart, 1984). This scenario is very speculative; it is also possible that the effect of CO_2-induced climatic change on Canadian agriculture could be catastrophic. Other parts of the world, however, and not as limited by temperature as Canada currently is, and third world countries may not be as capable of technological adaptation, so it is not clear whether the net global effect will be positive or negative. Studies by Blasing and Solomon (1983) and Decker et al (1986) suggest that American agriculture in the Great Lakes and Plains regions could successfully adapt to the climatic changes associated with a CO_2 doubling, although Gleick (1987) finds using hydrologic modelling techniques that significant reductions in summer soil moisture would occur in California for any of the GCM scenarios available. Even if some nations gain but the world looses as a whole, this is of concern to the possible beneficiaries since reductions in global food productivity could have serious repercussions for global stability and security.

A CO_2 doubling is currently not thought likely to provoke a sea level rise of more than 1 - 2 meters as a result of melting of continental ice and thermal expansion of the ocean . Even a one meter sea level rise would have significant impacts, however, as large populations in many of the world's great deltas would be subject to inundation and increased effects of storm surges. Figure 14 shows various scenarios of sea level rise as calculated by Hoffman (1984); note that even the low scenario has sea level rising by one meter during the next one hundred years. The land area affected by a sea level rise of 1 m would in many cases be greater than the area presently less than one meter above sea level, because erosion would tend to push the shoreline further inland until a new equilibrium beach profile was re-established. Protection of beaches of the U.S. East and Gulf coast against a one meter sea level rise may cost 10 to 100 billion dollars, plus a large amount of yearly maintenance (Vellinga, 1987). With a continued CO_2 increase beyond a doubling, larger sea level increases, and disproportionately larger human and economic costs, would be incurred. There have been some suggestions that the West Antarctic ice cap may be very sensitive to temperature increases and could unstably discharge into the ocean, causing a further 5 meters sea level rise (Mercer, 1978). The risk of this happening would also increase with increasing CO_2. Thus, prudence once again dictates that the CO_2 increase should be kept as small as possible.

Climatic warming already caused by increasing CO_2

If model results for an equilibrium climatic response to CO_2 doubling of 3.0 - 4.2 °C are correct then appreciable climatic warming should have already occurred as a result of the increase in CO_2 concentration since the beginning of the nineteenth century. The amount of warming depends on the pre-industrial CO_2 level, the predicted equilibrium warming, and the magnitude of the lag caused by the large heat capacity of the oceans. As well, other factors such as variations in volcanic activity or the solar constant may have also contributed to recent climatic change (Gilliland, 1982). Recent analyses suggest that a global mean warming of 0.5+0.2 °C occurred over the last 80-100 years and may be attributable to the increase of CO_2. Depending on the pre-industrial CO_2 level and the lag effect of the ocean, this warming is compatible with an equilibrium climatic response for CO_2 doubling of 1.0-4.5 °C (Wigley et al 1985; Wigley and Schlesinger, 1985). The fact that observed temperature changes may be compatible with climate model results does not mean that the CO_2 signal has been detected, however. It is possible that, with adequate monitoring, the climatic effect of the ongoing CO_2 increase will be clearly detectable by the year 2000 (MacCracken and Kukla, 1985).

Removal of CO_2?

Removal of CO_2 from the atmosphere in the face of continued or growing fossil fuel CO_2 emissions is not a feasible solution. The CO_2 concentration in fossil fuel power plant flue gas, on the other hand, is about 500 times greater than that in the atmosphere, and its removal is feasible but very expensive. Removal of 90 % of the flues gas CO_2 would increase production costs by 56 % to 100 %, capital investments by 70 to 150 %, and primary energy demand by 15 % (Steinberg et al 1984); the increased primary energy demand would increase the demand for coal and exacerbate the associated suite of environmental problems, including acid rain or sulphur removal problems. This is an example in which trying to solve one environmental problem associated with fossil fuel use, on a piecemeal basis without going to the root of the problem, can make other environmental problems associated with fossil fuels worse. Furthermore, only 0.73 of the 5.2 x 10^{15} g C currently released per year could be controlled in this way (Baes, et al 1980). Thus, reduced fossil fuel use is the only foreseeable means of significantly reducing the rate of build-up of atmospheric CO_2 due to fossil fuel CO_2 emissions.

1.3.2 Other trace greenhouse gases

A large number of other greenhouse trace gases besides CO_2 are increasing in concentration at a global scale (Wang et al 1986). Those directly or indirectly associated with fossil fuel use include methane (CH_4), nitrogen dioxide (N_2O), and tropospheric ozone. Estimated annual emission of CH_4 and N_2O from anthropogenically influenced sources are given in Tables 14 and 15, respectively. In the case of CH_4, the main emissions related with energy use are inadvertant venting of natural gas and releases associated with coal mining. One may expect the former

Table 14. Annual emission of CH_4 from anthropogenically influenced sources. Source: Bolle et al (1986).

Source	Emission Rate, 10^{12} gm C yr^{-1}
Ruminants	70-100
Rice paddies	70-170
Swamps/Marshes	25-70
Other biogenic sources	15-35
Biomass burning	55-100
Natural gas venting	30-40
Coal mining	35

Table 15. Annual emission of N_2O from anthropogenic sources. Source: Bolle et al (1986).

Source	Emission Rate, 10^{12} gm N yr^{-1}
Fertilizer	0.6-2.3
Increase of cultivated land area	0.2-0.6
Fossil fuel burning	1.9
Biomass burning	1 - 2

to decrease as natural gas becomes more expensive, but a large increase in the use of coal may lead to a large increase in methane emissions from this source.

Measurements of air bubbles trapped in polar ice cores indicate that the CH_4 concentration has roughly doubled since A.D. 1600, from about 0.8 ppmv to the current 1.6 ppmv. Currently the atmospheric concentration of CH_4 is increasing at 1 - 2 % per year (Wang et al 1986), with a corresponding doubling time of 70 - 35 years. A doubling of CH_4 is equivalent in its climatic effect to increasing CO_2 by 15 % from its present amount. The cause of the CH_4 increase is unknown, but probably involves some combination of (1) increased fluxes from rice paddies, ruminant animals, and termites, and (2) reduced effectiveness of sinks for atmospheric CH_4. The main sink for CH_4 is OH^-, whose concentration is tightly coupled to that of carbon monoxide (CO). There is growing evidence that atmospheric CO on a global scale may have increased by 1-2 percent per year or more over the last 1-3 decades (Seiler et al 1984; Khalil and Rasmussen, 1984; Rinsland and Levine, 1985), as a result of fossil fuel combustion, and modelling studies indicate that much of the observed CH_4 increase can be explained by a concurrent CO increase (Thompson and Cicerone, 1986). Whatever the causes of the CH_4 increase, the very fact of its increase reduces the allowable CO_2 increase and places a further constraint on fossil fuel use.

As seen from Table 15, fossil burning is likely to be the single largest anthropogenic source of N_2O. Over the period 1976-1980, Weiss (1981) measured a rate of increase of atmospheric N_2O of 0.2 percent per year. According to Weiss (1981), N_2O has an atmospheric lifetime in excess of 100 years and its major anthropogenic source is combustion of fossil fuels, with agricultural activity playing a minor role. Various catalytic converters are used to reduce emissions of NO_x from automobiles and industrial combustion, but at the expense of greatly increased emissions of N_2O (Weiss and Craig, 1976). Increased use of catalytic converters, particularly the popular platinum catalysts, will likely significantly increase the rate of N_2O emission. Here again we see an example in which an attempt to reduce one environmental problem - NO_x emissions in this case-without going to the root of the problem, can make a related environmental problem worse.

Figure 15, taken from Ramanathan et al (1985), shows the cumulative equilibrium climatic warming associated with projected increases of CO_2 and other greenhouse trace gases between 1980 and 2030 for a set of scenarios of increase in CO_2 and other trace gases. Due to the thermal inertia of the oceans, the actual climatic response would lag the equilibrium response by 1-3 decades. Carbon dioxide was assumed to reach a concentration of 450 ppmv which, according to Figure 10, requires a growth in CO_2 emissions of 1.5-1.6 percent per year. Projected increases of all the known greenhouse gases would increase the CO_2 greenhouse warming by a further 50 - 350 percent, with the most likely effect thought to be a doubling of the climatic response caused by CO_2 alone. Emissions of some of these gases, such as chlorofluorocarbons, can and probably will be regulated independently of fossil fuel use, largely out of concern for the stratospheric ozone layer. Other trace gases such as CH_4, tropospheric ozone, and N_2O, are directly or indirectly dependent on fossil fuel use and could increase the CO_2 warming by a further 20 to 120 percent, with the most likely effect thought to be an increase by 50 percent of the climatic response caused by CO_2 alone. Thus, optimistically assuming that all uses of chloroflorocarbons (which are the most important greenhouse gases not associated with fossil fuel use) will be quickly regulated, a further CO_2 increase of about 160 ppmv with the associated increase of CH_4, tropospheric ozone, and N_2O assumed by Ramanathan et al (1986) would be equivalent in terms of its climatic impact to a CO_2 increase of 240 ppmv and would give an equivalent CO_2 concentration of about 580 ppmv, which would

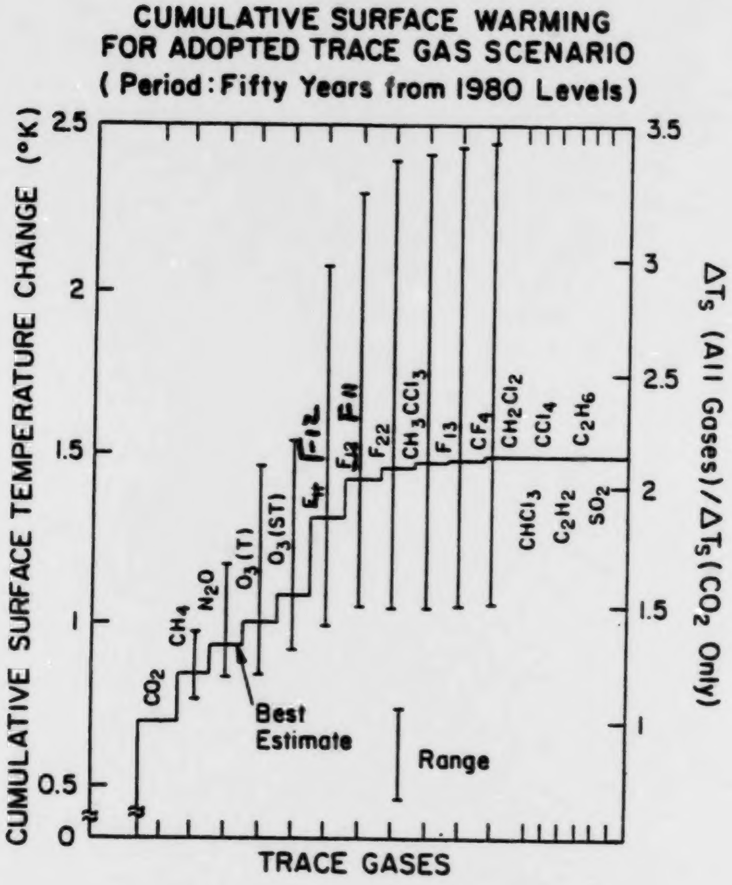

Figure 15. Cumulative equilibrium surface warming from increases in CO_2 and other greenhouse gases projected to occur between 1980 and 2030 as projected and calculated by Ramanathan et al (1985).

amount to a doubling of the CO_2 concentration above a likely mid-nineteenth century concentration of 290 ppmv. Thus, in order to have the equivalent of a CO_2 doubling, the CO_2 concentration may have to be limited to no more than 500 ppmv. As summarized by Laurmann (1985),

> "if current estimate of growth rate and climatic effect of the OGG's [other Greenhouse Gases] are accepted, immediate actions to implement the introduction of nonfossil fuels are needed to avoid significant climatic impact. The latter is defined as a global temperature rise of 2.5 °C by the mid 21st century."

1.3.3 Summary of climatic and physical impacts of greenhouse gases

Estimated ultimately recoverable fossil fuel resources are large enough to increase the atmospheric CO_2 concentration by 3 to 11 times above the pre-industrial level of 290 ppmv. There has been a strong downward trend in projected future rates of growth in energy demand and in the rate of emission of CO_2 from fossil fuel use, with early studies projecting growth rates for CO_2 emissions of 2-4 percent per year with a doubling of atmospheric CO_2 by the middle of the next century, and the most recent studies projecting growth rates of 1 percent per year or less and a CO_2 doubling by the end of the next century or later. However, other strong greenhouse gases are also increasing in concentration, and the cumulative effect of these gases plus CO_2 could be to give the equivalent of a CO_2 doubling as early as 2020-2030. Positive feedbacks involving the carbon and methane cycles could lead to further equivalent increases of CO_2 even after anthropogenic emission stopped. A CO_2 doubling or its equivalent, although small compared to the increase which could occur if all recoverable fossil fuel resources were used, would have significant effects on climate. The most likely equilibrium response is a 2-3 °C globally averaged warming but 2-3 times larger in polar regions, and reduced summer soil moisture and increased drought in mid-latitudes, where most of Mankind's food is grown. Given Mankind's ability to adapt, there is a possibility that we can cope with the climatic change associated with a small CO_2 increase, perhaps even as large as a doubling, and the net effect might even be positive. It is quite clear, however, that it would be increasingly difficult to adapt to progressively larger changes. Given the uncertainties and risks associated with even a CO_2 doubling, it is of the utmost urgence that the CO_2 increase be limited to a doubling or even less. Thus, climatic considerations alone imply that we will not be able to use more than 10 - 30 % of the total recoverable fossil fuel reserves, and that as liquid fuels run out in the next few decades we will have to phase in non-fossil fuel energy sources, rather than undertaking massive development of synthetic liquid fuels from coal, shale oils, and tar sands. Given concurrent increases in other greenhouse gases, and optimistically assuming that chlorofluorocarbon emissions will be quickly reduced to an insignificant level out of concern for the ozone layer, the CO_2 concentration would have to be limited to 500 ppmv or even less in order to have the equivalent of no more than a CO_2 doubling.

1.4 Potential effects of fossil fuel use on stratospheric ozone

Nitrous oxide (N_2O) and carbon monoxide (CO) are two trace gases associated with fossil fuel use which could directly (in the case of N_2O) or indirectly (in the case of CO) lead to a reduction in the amount of stratospheric ozone. As previously noted, there is growing evidence that atmospheric CO may be increasing by 1-2 percent per year. Reaction of CO with OH^- is the main sink for OH^-, which in turn is an important sink for many tropospheric (lower atmosphere) trace gases which can affect stratospheric ozone chemistry. As the atmospheric OH^- concentration decreases the concentration of these gases would increase, allowing them to migrate into the stratosphere where they could affect ozone (Crutzen, 1983). Any changes in OH^- or O_3 resulting from increased CO could very well be partly counteracted by reactions involving NO (Crutzen, 1983). Although there are stronger potential anthropogenic effects on stratospheric ozone, a full evaluation of the environmental impact of fossil fuel use must include the possibility of perturbations to the stratospheric ozone layer. Since the atmospheric lifetime of CO is only 2-6 months, reduced fossil fuel use would quickly lead to a reduction in its concentration-in contrast to the case of CO_2.

1.5 Policy options and constraints as conventional liquid fuels are depleted

The International Institute for Applied Systems Analysis (IIASA) recently carried out a comprehensive study of global energy supply and demand, and produced two scenarios - a high and a low scenario - for total global energy demand to the year 2030 (Hafele, 1981). In the low scenario global energy demand grows by an average of 1.5 percent per year between 1975 and 2030, while in the high scenario it grows by an average of 2.5 percent per year. According to these energy scenarios, global production of conventional oil will peak between 1990 and 2010, while the production of natural gas will peak between 2000 and 2020, with steady declines thereafter as supplies are depleted and extraction becomes more difficult and costly. Khandani and Rose (1985) independently estimated that oil and gas resources will be largely depleted by 2010, even if prices and reserves double by then. As previously indicated, consumption of the recoverable liquid fossil resources will increase atmospheric CO_2 by about 50-90 ppmv which, by itself, should not pose a significant climatic hazard. As liquid fuels are depleted Mankind will be confronted with the need to either undertake massive development of synthetic fuels from solids, primarily coal, or to find non-fossil fuel replacements for liquid and gaseous fuels. The first option would accelerate the buildup of atmospheric CO_2 to levels which could reach several times the present concentration and would eventually lead to unacceptable climatic change, and would therefore be a short-term solution. Indeed, even the current rate of solid fuel consumption would have to be reduced along with a supply-driven phasing out of conventional liquids and gaseous fuels if the atmospheric CO_2 concentration is to be limited to 500 ppmv. As well, problems of acid rain and urban air pollution associated with the use of fossil fuels would persist if synthetic fuels were produced. Thus, a desire to reduce the rate of CO_2 increase and minimize air pollution problems may serve as a strong constraint on the increased use of coal as liquid fuels are depleted.

There are three additional strong environmental constraints which are likely to severely limit the extent to which the use of coal can be increased: (1) water limitations, (2) disposal of sulphur wastes, (3) land subsidence where underground gasification is used to extract coal.

According to the IIASA study, coal production increases by factors of 1.5 and 2.6 in the USSR and USA respectively between 1975 and 2030 for the low energy scenario, and by factors of 4 and 5 for the high energy scenario. Alcamo (1984) analyzed water requirements in the USA and USSR for the high scenario and concluded that, although there would be no absolute shortage of water assuming present day river flows for the high scenario, there would be severe competition with other uses of water. Alcamo (1984) assumed very efficient use of water for coal development, but estimates that actual water requirements could be 50 % greater than he assumed. There is no mention of the possibility of changes in regional hydrologic balances associated with CO_2 induced climatic warming, which is surprising in light of the climatic models results cited above which indicate possible large reductions in water availability in coal producing regions. Runoff is a residual between precipitation and evaporation and is therefore highly sensitive to a change in either. It would be most unwise to plan major, water intensive energy projects under the assumption that the hydrologic balance will not change, particularly when these very projects would accelerate the rate of climatic and hydrologic change!

Bockris (1980) estimates that the average sulphur content of American coal is 5 %. Removal of 99 % of the sulphur from the coal needed by a 1000 MW plant would produce a sulphur volume of 10^5 m^3 yr^{-1}, which would cover a city block to a height of 10 meters. The present entire energy supply for the USA would produce about a million such blocks per year, creating a significant disposal problem if coal were to become the primary energy source.

About 6 percent of US coal resources could be recovered by strip-mining and deep-mining techniques according to Bockris (1980); underground gasification or some other yet-to-be-developed technology would be needed for the remainder. In situ gasification of coal, however, would lead to problems of ground subsidence, thus posing a further constraint on coal use.

1.6 Strategies for limiting CO_2 increases

Perry et al (1982) extended the IIASA low and high total energy demand scenarios cited above to the year 2100 and determined the rates at which non-fossil fuel energy sources would have to grow in order to keep atmospheric CO_2 concentration below given thresholds while still providing the same total energy supply as in the extended IIASA scenarios. The low energy scenario sees global energy demand increasing by about a factor of 4 by the year 2100, from a current value of about 10 TW to about 40 TW, while the high scenario sees global energy demand increasing by a factor of 6, to about 60 TW. In the low IIASA scenario energy demand grows by an average of 1.5 percent per year, which is comparable to the median energy growth rate for 1975-2075 obtained by the Edmonds et al study (1986), cited earlier. However, a number of studies have shown that if all possible presently available cost-effective technological improvements were made, significantly smaller growth in global energy demand or even a decrease in global energy demand could occur alongside significant economic growth in both the developed and developing world (Lovins, 1980). Nevertheless, the required growth of non-fossil fuel energy supply as calculated by Perry et al (1982) for both IIASA scenarios and for a 515 ppmv upper limit for atmospheric CO_2 is shown in Figure 16. An important parameter in their study is the Action Initiation Time (AIT) - the time at which agreed upon policies to limit CO_2 growth begin to be implemented at a global scale. Figure 17 shows the required rate of installation of non-fossil fuel energy sources for the high energy scenario with a 500 ppmv CO_2 limit and for the low energy scenario with a 600 ppmv CO_2 limit, both with an AIT in the year 2000. The most important conclusion from these results is that, with a CO_2 limit of 500 ppmv, actions should be taken by the turn of the century in order to avoid excessively large rates of installation of non-fossil fuel energy sources. As stated by Perry et al,

> "to prevent CO_2 concentrations from rising above 500 ppmv - even though this would not occur for another half century at least - would be difficult, requiring

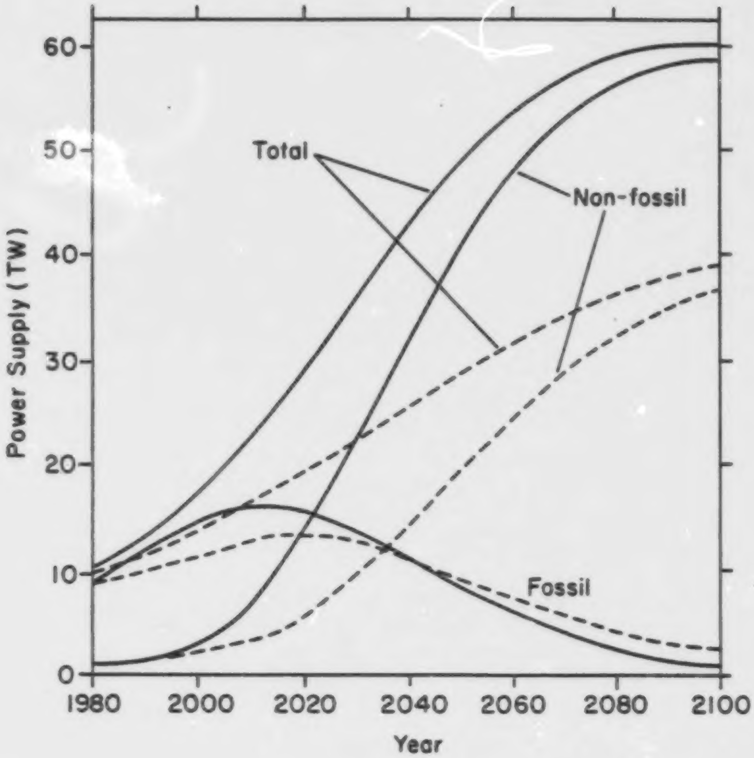

Figure 16. Total global energy demand for the high and low IIASA energy scenarios as extended by Perry et al (1982) to the year 2100, and separate energy production rates for fossil and non-fossil energy sources required in order to keep the atmospheric CO_2 concentration from rising above 513 ppmv. Solid lines: high energy scenario with an action initiation time (AIT) of 1990; dashed lines: low energy scenario with an AIT of 2000.

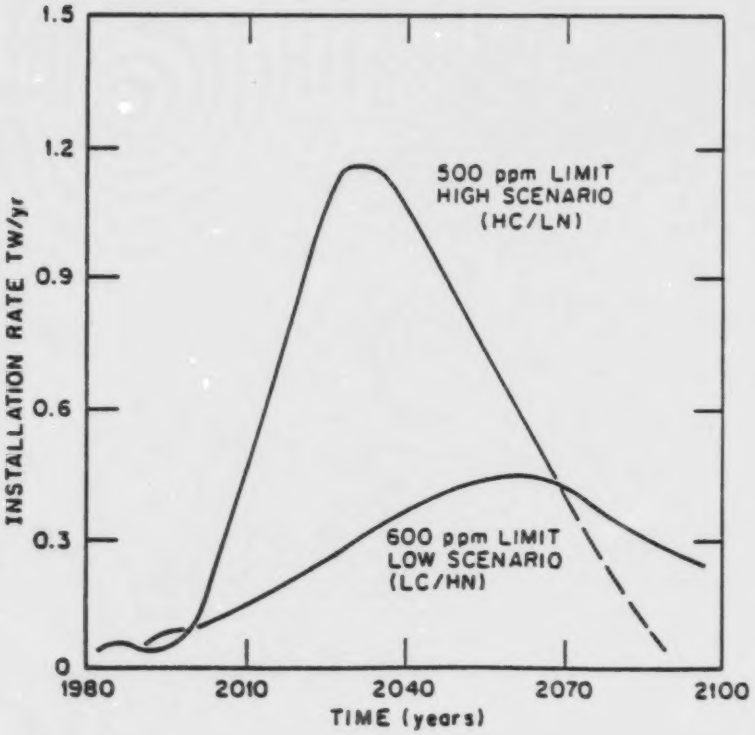

Figure 17. Required rate of installation of non-fossil fuel energy supply capacity as computed by Perry et al (1982) for the high total energy growth scenario with a 500 ppmv CO_2 limit, and for the low total energy growth scenario with a 600 ppmv limit, both with an action initiation in the year 2000.

early and aggressive action, especially for the higher initial coal growth rates"

The longer action is delayed the more difficult the transition will be, although reduced growth in energy demand through vigorous promotion of energy conservation is a significant factor, both in giving more time for the transition and in reducing the magnitude of required non-fossil fuel energy supplies.

The results of Perry et al (1980) depend on a carbon cycle model to compute atmospheric CO_2 buildup for various emission scenarios. Although different carbon cycles models give essentially the same results when an exponential increase in CO_2 emissions is assumed, the models show greater differences if decreasing CO_2 emissions are assumed. This is seen by comparing Figure 18, taken from Laurmann and Spreiter (1983), with Figure 9 and 10, taken from the same authors. In Figure 18 an exponentially decreasing CO_2 concentration at a rate of 1 percent per year is assumed. A larger rate of decrease would be needed to keep the CO_2 concentration from rising above 500 ppmv, in which case the difference between the models would be larger. Thus, if strategies to limit the CO_2 increase are adopted then uncertainties in carbon cycle models will have to be reduced in order to reliably estimate the rate at which fossil fuels must be phased out in order to satisfy a given CO_2 limit.

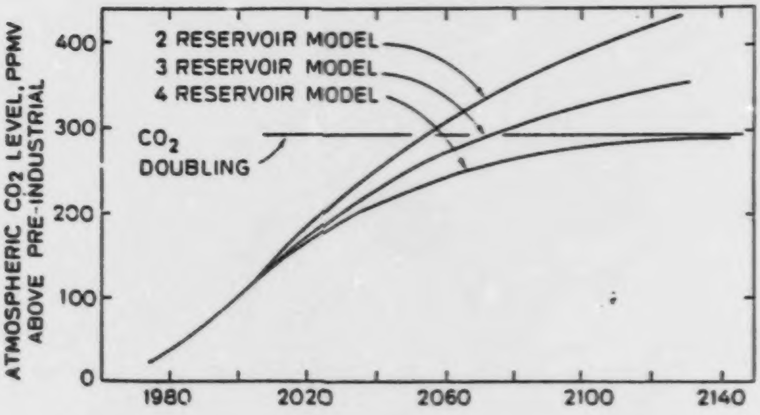

Figure 18. Comparison of the increase of atmospheric CO_2 above a concentration of 300 ppmv as computed by Laurmann and Spreiter (1983) for three different carbon cycle models assuming an exponentially decreasing CO_2 release after 2000 at a rate of 1 % per annum.

2. POTENTIAL ROLE OF HYDROGEN IN SOLVING FOSSIL-FUEL RELATED ENVIRONMENTAL PROBLEMS

A number of alternative energy sources is available which, collectively, could replace fossil fuels. Among these are further development of hydroelectric and nuclear energy, various types of solar energy installations, biomass energy, and geothermal, wind, and tidal energy[3]. A major problem with these alternative energy sources is that the energy carrier that they produce-electricity - cannot be stored, and would not easily meet transportation energy needs, where liquid fuels are used almost exclusively because of their portability. What is needed is an alternative energy carrier or energy currency, and the most likely such carrier is hydrogen (H_2). Hydrogen would not represent an energy source as it requires an energy input to manufacture it but, once manufactured, could be used in all the ways in which fossil fuels are currently used - to generate electricity, run automobiles, fly airplanes, for space heating, in appliances which currently use natural gas, and as a reducing agent in many industrial applications. In 1980 a Canadian Parliamentary committee concluded that in 50 years hydrogen and electricity will be the major energy carries in Canada, and that hydrogen is the best fuel for a noncarbon-based energy system (Lefebvre, 1981). More recently, a Canadian study by a ministerial advisory group on hydrogen opportunities recommends that a major national program involving hydrogen production, distribution, and end-use be established in Canada (Advisory Group on Hydrogen Opportunities, 1987). The term hydrogen economy has been coined to describe an economy using hydrogen derived from renewable, non-fossil fuel energy sources.

2.1 Environmental and health benefits of a hydrogen-based energy system

Benefits in a full hydrogen economy

Use of hydrogen produced from non-fossil fuel energy sources would eliminate the major environmental problems of urban air pollution, acid rain, and the CO_2 increase discussed above. The only direct combustion products of hydrogen are energy and water, although minor amounts of NO_x are produced from atmospheric nitrogen under conditions of high temperature combustion. As discussed below, thermodynamic efficiencies using hydrogen in fuel cells are several times greater than when hydrogen is used in an internal combustion engine, which in the long run makes them the most likely end use technology for hydrogen in automobiles. When used in fuel cells, hydrogen is completely non-polluting. Urban air pollution would thus be essentially eliminated in a hydrogen economy. Hydrogen from non-fossil fuel energy sources could replace the present coal-fired electrical generating plants and could be used as a reducing agent in place of coke (derived from coal) in many ferrous metallurgical processes (Bockris, 1980; Antonioli, 1982), thereby eliminating the major sources of SO_2 and, coupled with the near or total elimination of NO_x from automobiles, eliminating the acid rain problem. Hydrogen could also be used as a heating and cooking fuel in individual households and could be introduced to great advantage in rapidly developing countries such as China where coal is currently being used for these purposes, thereby eliminating local but widely dispersed pollution and health problems (Zweig, 1987). Finally, a hydrogen-based economy would eliminate fossil fuel emissions of CO_2, thereby eliminating the single largest anthropogenic greenhouse effect and, coupled with regulation of other strong greenhouse gases where possible, averting significant and eventually catastrophic climatic change.

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[3] As well, increased efficiency of energy production and end use can be considered an equivalent energy source and has enormous potential.

The manufacture of hydrogen by electrolysis of water using solar, hydro, or nuclear generated electricity would produce oxygen as a bi-product. This oxygen would be comparatively cheap, and Bockris (1980) lists a number of pollution treatment processes where bi-product oxygen could be used to great advantage. Among these are: (1) aerobic sewage treatment, where use of pure oxygen rather than air would reduce the required plants size by a factor of 3-4; (2) injection of oxygen into de-oxygenated lakes and rivers, and (3) use of pure oxygen rather than air in incinerators, which would reduce emissions of pollutants.

Benefits during the transition to a hydrogen economy

Prior to the development of a full hydrogen economy, using hydrogen derived from non-fossil fuel sources, there are three ways in which hydrogen could be used in conjunction with the use of conventional liquid fuels or the manufacture of synthetic liquid fuels from solid fossil fuels in such a way as to reduce urban air pollution problems, slow down the rate of atmospheric CO_2 increase, and facilitate the transition from a carbon based to a hydrogen based energy system:

(1) Tar sands, shale oils, and coal are deficient in hydrogen compared to liquid fuels. Production of liquids thus requires addition of hydrogen, which in the case of coal can come from the solid fuel itself through gasification (with an associated release of CO_2), or can be provided from an external source. The CO_2 emission rates given in Table 11 for gasification and liquefaction of coal are for processes in which the required

hydrogen is derived from the coal itself. Production of hydrogen from coal for coal liquefaction generally consumes 20-30 percent of the total coal input (i.e.: Bowman and du Plessis, 1986). Use of non-fossil fuel hydrogen would reduce the CO_2 emission for synthetic liquids by 20-30 percent, giving emission rates as low as that given for petroleum in Table 11. In addition to reducing CO_2 emission, use of non-fossil fuel hydrogen would reduce the quantity of coal needed and the associated environmental and health effects of coal extraction and transportation.

(2) Hydrogen produced from coal could be used instead of synthetic fossil fuels derived from coal in automobile internal combustion engines or aircraft jet engines, or could be used to generate electricity in fuel cells instead of through the direct combustion of coal in thermal generating plants. As discussed below, these uses of coal would require less coal then converting the coal to synthetic liquids or burning it directly in a thermal generating plant, resulting in lower CO_2 emissions. Furthermore, it may be feasible to remove some or all of the CO_2 at the time of hydrogen production and directly bury it in the deep sea (Blazek et al 1986), whereas this cannot be down with CO_2 released from combustion of synthetic fuels manufactured from coal. If hydrogen were produced close to the sites of coal extraction (to minimize coal transport costs), then air pollution would be reduced in urban centres (where high concentrations of people occur) at the expense of increased air pollution at the sites of hydrogen production (where low concentrations of people occur), thus reducing the net health impact of fossil fuel use.

(3) Hydrogen can be used as an additive to gasoline and diesel powered automobiles and light aircraft, significantly reducing emissions of CO, NO_x, and unburnt hydrocarbons while increasing fuel economy. According to Soviet tests reported by Stolyarevskii and Chuveliov (1987), addition of 10 percent hydrogen by mass to gasoline-fueled automobiles reduces emissions of CO by 15 %, hydrocarbons by 13 percent, and NO_x by 6 percent while decreasing gasoline consumption by 50 percent, while 3.5 percent hydrogen in diesel-fueled vehicles reduces soot emissions by 40 to 100 percent. Particularly large reductions of urban air pollution would be possible in many European and other cities where a large percentage of the automobiles is diesel-fuelled. According to Menard et al (1976), addition of hydrogen to gasoline in light aircraft can reduce fuel consumption by 20 % while reducing emissions of CO by 92 percent, NO_x by 20 percent, and hydrocarbons by 36 percent.

In addition to slowing the increase of atmospheric CO_2, reducing urban air pollution problems, and reducing the overall demand for coal compared to alternative scenarios using synthetic fuels, the transitional uses of non-fossil fuel hydrogen outlined above would help to facilitate gradual development of the extensive production, distribution, and storage facilities for hydrogen, and the associated advances in technology, which would be needed in a full hydrogen economy.

2.2 Production of hydrogen

2.2.1 Fossil fuel sources

Most hydrogen used today is produced by either methane reforming, partial oxidation of oil, or coal gasification, which can be represented as follows (Gupta, 1983):

Methane reforming: $CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$

Oxidation of oils: $CH_{1.8} + 0.98H_2O + 0.51O_2 \rightarrow CO_2 + 1.88H_2$

Coal gasification: $CH_{0.8} + 0.6H_2O + 0.7O_2 \rightarrow CO_2 + H_2$

The energy content of the product hydrogen is less than that of the input fuel (54 percent in the case of coal), so that global energy supplies would be diminished if hydrogen from gaseous, liquid, or solid fossil fuels were to replace the type of fossil fuel from which it was manufactured. Methane reforming is currently the cheapest of all methods, fossil fuel or non-fossil fuel, for manufacturing hydrogen and almost all of the hydrogen used today is produced by this method. Of all the fossil fuel based methods, methane reforming results in the smallest CO_2 emissions and coal gasification the largest emissions, but, as noted above, coal gasification to produce hydrogen would still result in smaller CO_2 emissions than using coal to produce synthetic oil and gas, and so would be helpful as an intermediate step in the transition to non-fossil fuel based methods of hydrogen manufacture.

It is important to note that hydrogen produced from fossil fuels is "dirty" hydrogen in the sense that it contains impurities of CO and, if derived from coal or residual oil, sulphur. These impurities would limit the potential uses of fossil fuel-derived hydrogen, as explained below. Non-fossil fuel hydrogen, on the other hand, is "clean" hydrogen, both in the sense that it contains no impurities, and in the sense that its production would be largely or entirely non-polluting (see Section 2.7).

2.2.2 Non-fossil fuel sources

Hydrogen can be produced by electrolysis of water using electricity which could be provided by (1) off-peak hydro-electric energy, (2) nuclear energy, (3) solar voltaic energy, (4) ocean swell and wave energy conversion (OSWEC), (5) ocean thermal energy conversion (OTEC), and (5) wind, tidal, and geothermal energy sources. Electricity to hydrogen conversion efficiencies of electrolysers are as high as 80 percent, and efforts are underway to improve this efficiency even further (i.e.: Crawford and Hufnagl, 1987). A sixth, non-electrolytic method for producing hydrogen is to use photosynthetic bacteria.

Hydro-electric energy

The fundamental problem with electricity as an energy carrier is that it cannot be stored. Thus, hydro-electric generating facilities are forced to operate at less than capacity during none-peak demand, resulting in wasted capacity, or are designed to meet only base load demand, with oil or coal-fired generating plants to meet peak demand (These plants are inefficient - typical efficiencies are only 0.27 - 0.31). Because hydrogen can be stored and later recombined with oxygen to produce electricity, hydrogen could be produced during off-peak hours and used during peak hours, thereby displacing supplemental fossil fuel sources of electricity. Electrolysis plants have efficiencies in excess of 80 percent, and can be operated from 10 to 100 % of capacity with little loss of efficiency and so are ideal for load levelling (Hammerli, 1984). Alternatively, in present or future hydro-electric facilities designed to meet peak demand, off-peak capacity could be used to produce hydrogen for use in the transportation sector. Table 16 gives estimates of the unexploited hydro-electric potential for various countries as compiled by Antonioli (1982). He estimates that the global unexploited potential is about 4000 TWh, which is equivalent to 34 percent of the world consumption of crude oil in 1978. There are environmental costs in developing hydro-electric energy which would have to be traded against other alternatives, so it is not clear how much of this potential it would be desirable to develop. Note that, with hydrogen as an energy carrier and storage medium, the vast hydro-electric potential of Greenland could be exploited.

In the case of Canada, the 1984 electricity generating capacity was 90.4 GW, of which 55.0 GW were hydro-electric and 7.7 GW were nuclear (National Energy Board, 1986). According to Robinson (1987a), 9.5 GW of hydro-electric generating capacity were under construction in Canada at the end of 1981, and he estimates the remaining technically and economically feasible hydro-electric capacity to be 66.6 GW out of a total technically recoverable capacity estimated at 106.4 GW. According to Hammerli (1984), a 9.4 GW electrolysis plant operating at 0.9 capacity and an efficiency of 82.2 percent could produce hydrogen with the energy equivalent of 100,000 bpd (barrels per day) of oil. Awad and Veziroglu (1984) estimate that hydrogen could be used 22 percent more efficiently than oil in internal combustion engine (ICE) powered cars, and 33 percent more efficiently in fuel cell

Table 16. Estimated unexploited hydroelectric potential, GW (1 GW = 8.766 TWh/yr), as compiled by Antonioli (1982). Note that the estimated potential for Canada is considerably smaller than estimated by the authors cited in the text.

Country	Potential	Country	Potential
Zaire	71.5	Mexico	7.8
Greenland	57.0	Chile	6.6
China	50.7	Venezuela	6.0
Brazil	35.9	Norway	4.3
USSR	30.6	Gabon	4.3
India	21.5	Pakistan	4.2
Indonesia	14.4	Papuasia	3.8
Malaysia	10.4	Canada	3.5

Global total: 456 GW

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powered cars after accounting for the weight penalties occurring because hydrogen fueled cars would be heavier. Thus, if the estimated remaining exploitable hydro-electric capacity in Canada of 66.6 GW were used to produce hydrogen for use in fuel cell powered cars, about 1 million bpd (barrels per day) of oil could be displaced. Total use of oil in Canada in 1984 was 1.4 million bpd (National Energy Board, 1986). Since there also exists enormous potential for energy savings in Canada by implementing only currently available, cost-effective technologies (Robinson, 1987b), demand of non-fossil fuel energy for current uses could be kept constant for several decades even with strong economic growth, and most of the current oil demand in Canada could be meet with hydrogen produced from hydro-electric facilities alone.

Nuclear energy

To the hydro-electric potential discussed above must be added the possibility of using existing unutilized nuclear generating capacity or dedicated nuclear power to produce hydrogen. There is great public concern about the safety of nuclear energy, and continued or expanded use of nuclear energy requires vigorous implementation of stringent safety precautions. It is also difficult to defend expanded use of nuclear energy before finding a socially, politically, and environmentally acceptable method for longterm disposal of nuclear wastes, a difficult and still unresolved problem. If the disposal and safety concerns can be resolved, then nuclear energy could play an important role in a hydrogen economy.

Two options are currently available for the production of hydrogen from nuclear-generated electricity: (1) conventional low temperature electrolysis, such as would also be used with hydroelectric or some of the other energy sources described below, and (2) high temperature water vapour electrolysis. The latter is an emerging technology which has received considerable attention and been tested at a small scale in West Germany (Doenitz and Schmidberger, 1982). The conversion efficiency from thermal energy (whether from a nuclear reactor or fossil fuel plant) to electricity is 31 to 38 percent, and with an electrolysis efficiency of 82 percent, the net conversion efficiency from thermal energy to hydrogen is only 25 - 31 percent. In high temperature water vapour electrolysis some of the waste heat is used with the electricity to generate hydrogen with efficiencies of up to 50 percent. Energy in the form of hydrogen could thus be produced more efficiently from primary nuclear energy than energy in the form of electricity.

Solar energy

Among the options available for the production of hydrogen using solar energy are (1) photovoltaic generation of electricity coupled with electrolysis, and (2) thermal solar energy, whereby solar energy is concentrated with parabolic dishes to produce steam and generate electricity, followed by electrolysis.

Solar energy to produce hydrogen has been a subject of considerable research in West Germany, and involves cooperative research and demonstration projects with Saudi-Arabia (Fischer, 1986). Voigt (1984) discusses the characteristics of a photovoltaic (solar voltaic) facility in North Africa capable of meeting 4 percent of the total secondary energy needs for West Germany, while Nitsch (1986) provides further estimates of size, material, and energy requirements for the construction of solar-hydrogen production systems. The main obstacles in using solar voltaic energy to produce hydrogen are in the cost of silicon and the substantial requirements of concrete and steel needed to support the solar cell modules, and in the need to design solar cell modules such that the materials used in them can be separated and recycled. The U.S. Department of Energy is funding a program with the goal of reducing the cost of silicon solar cells by a factor of ten, which would bring their cost close to that felt to be necessary before solar voltaic energy could be used to manufacture hydrogen. Improvements in the solar energy to electricity conversion efficiency could substantially reduce the required solar energy collector area and associated material requirements and costs. Current silicon solar cells utilize photons in a single energy band, have a theoretical efficiency of 25 percent, and have attained efficiencies of 12-15 percent so far (Fischer, 1986). An important emerging technology is the development of multi-band solar cells, capable of utilizing photons in a number of adjacent bands, and having theoretical efficiencies of up to 45 percent. Multi-band solar cells are currently the subject of considerable research in West Germany (Fischer, 1986).

The largest pilot plant for the generation of electricity from thermal solar energy is a 10 MW plant in Barstow, California. Operating temperatures attain 800 °C; if process heat were used simultaneously with electricity in high temperature water vapour electrolysis, then, as discussed above in the context of nuclear energy, conversion efficiencies of up to 50 percent could be obtained. A combined solar thermal - high temperature water vapour electrolysis system would likely be the most efficient way of generating hydrogen from solar energy.

The great advantage of a combined hydrogen-solar energy system is that use of hydrogen as an energy carrier overcomes the supply-demand mismatch problem which currently limits schemes to use solar energy. Two emerging technologies, multi-band solar voltaic cells and high temperature water vapour electrolysis, promise to dramatically improve the efficiency with which solar energy can be converted to hydrogen, thereby reducing costs and material and land area requirements. Production of hydrogen using solar energy would be most favorable in tropical and subtropical countries, would be more geographically dispersed than the bulk of current oil supplies, and could do much to reverse the widening North-South gap.

OSWEC

Woodbridge (1983) discusses the Ocean Swell and Wave Energy Conversion (OSWEC) concept for producing hydrogen. With this method the energy of the vertical component of ocean waves is converted to a DC voltage and used in an electrolyser to produce hydrogen. Desalinization and purification of the input feedwater would consume less the 2 percent of the total energy used. Woodbridge envisages 50-200 MW systems using OSWEC.

OTEC

Another promising concept for manufacture of hydrogen fuel is Ocean Thermal Energy Conversion (OTEC). This concept uses the temperature difference in the tropical ocean between the ocean surface and water one hundred or more meters deep. Discussions of this concept may be found in Lavi (1985), Lavi and Jopling (1985), and Kamogawa (1985).

Wind, tidal, and geothermal

In local regions wind, tidal, or geothermal energy could provide a significant fraction of the local energy needs if hydrogen were used as an energy carrier. As with solar energy, use of hydrogen overcomes the supply-demand mismatch problem which would otherwise greatly limit the usefulness of these energy sources. Robinson (1987a) estimates the ultimately recoverable tidal energy resource in Canada as 40 GW, with 2 GW being recoverable under current economic conditions. He estimates the ultimately recoverable wind energy resource in Canada as 17,400 GW out of a physical resource base of 2.6 million GW. If only 0.1 percent of the estimated recoverable resource were converted to hydrogen with 80 percent efficiency and used in fuel cell powered automobiles with a net efficiency advantage over gasoline powered automobiles of 33 percent, it would displace about 260,000 bpd of oil.

Photosynthetic bacteria

Photosynthetic bacteria such as *Rhodopseudomonas capsulata* release hydrogen and could metabolize municipal waste effluent (Vezeriglu, 1987). The light to hydrogen conversion efficiency is 5 percent, which is comparable to current solar voltaic efficiencies for generating electricity (one step removed from hydrogen), but could possibly be increased through genetic engineering.

2.3 Uses of hydrogen

2.3.1 Current uses

In Canada the total demand for hydrogen in 1978 was 11.8 x 10^9 m^3, equivalent to 151 x 10^{15} J or a power of 4.8 GW over the entire year (Hammerli, 1984). Of this output, 43 percent was used in the manufacture of ammonia, 33 percent in oil refining, 12 percent in manufacture of synthetic liquid fuels, and 9 percent in the manufacture of methanal. As conventional oil supplies are depleted the remaining oil will require proportionately more hydrogen for refining purposes, and total demand in Canada from this sector is expected to double by 2025 in spite of declining production of petroleum products (Hammerli, 1984). As well, the use of hydrogen in synthetic fuels is expected to grow from 1.7 x 10^9 m^3 in 1980 to 19 x 10^9 m^3 by the year 2025. These projections have served as a catalyst for research and development of efficient electrolytic production of hydrogen using nuclear energy (Hammerli, 1983; Taylor, 1984; Crawford and Hufnagl, 1987), which is expected to begin replacing methane-derived hydrogen in Canada by the 1990's (Barnstable and Petrella, 1982; Hammerli, 1984). Demand for hydrogen for the U.S. space program is also expected to grow dramatically over the next 25 years.

There is a growing interest in methanol (CH_3OH) as an alternative fuel for automobiles, as current automobiles can run on methanol with very little modification, although methanol-fueled vehicles may have difficulty meeting anticipated emission standards. Methanol can be produced from methane where available, but could also be manufactured from electrolytic hydrogen (Advisory Group on Hydrogen Opportunities, 1987). Significant use of methanol as a vehicular fuel would create an enormous market for hydrogen, and would circumvent the handling, storage, and initial distribution problems associated with the direct use of hydrogen.

In sum, demand from current uses of hydrogen is expected to grow dramatically over the next 20-40 years and, in Canada and perhaps elsewhere, will be increasingly supplied by non-fossil fuel energy sources. This will help to lay the necessary foundation for development of new uses of hydrogen in sectors where fossil fuels are currently used.

2.3.2 Future uses

The fuel cell will play a key role in most applications where hydrogen can displace fossil fuels, and its further development is essential to the evolution of a hydrogen economy. Table 17 lists the four main types of fuel cells in existence today, their operating temperatures, current conversion efficiencies from hydrogen to electricity, estimated attainable efficiencies, and theoretical efficiencies. By making use of the waste heat from fuel cells in applications explained below, even greater combined thermal and electric conversion efficiencies could be attained. Awad and Veziroglu (1984) state that efficiencies of 80-90 percent may be attainable in advanced fuel cells. By comparison, conversion efficiencies for some common uses of fossil fuels are as follows: coal to electricity in a thermal generating plant: 33-35 percent (Awad and Veziroglu, 1984); gasoline to mechanical energy in an internal combustion engine: 12 percent (Kukkonen, 1982). The conversion efficiency of hydrogen to electricity is thus twice that of coal to

Table 17. Types of fuel cells, operating temperatures, current efficiencies, likely attainable efficiencies, and theoretical efficiencies. Operating temperatures from Selman (1981), phosphoric acid and molten carbonate efficiencies from Cheng et al (1986).

Type	Operating Temperature	Efficiency Current	Attainable	Theoretical
Phosphoric acid	80-200 °C	40	50	94
Alkaline	80-300 °C			
Molten Carbonate	500-800 °C	45	55	94
Solid oxide electrolyte	> 1000 °C			

electricity, whereas the efficiency of hydrogen in fuel cell powered automobiles would be 4-5 times that of gasoline. Alkaline fuel cells, which have operating temperatures suitable for use in automobiles, require pure hydrogen. Molten carbonate fuel cells, on the other hand, require some CO impurity for their operation (UTME, 1980). Phosphoric acid fuel cells can run on dirty hydrogen such as would be derived from fossil fuel sources. Alkaline fuel cells require precious metal (such as platinum) catalysts, whereas the need for precious metals decreases with operating temperature as other fuel cells are considered (UTME, 1980).

Public utility electricity generation

Hydrogen could be produced at hydro-electric and nuclear power facilities by electrolysis when excess capacity is available, and latter used in fuel cells to generate electricity when needed, thereby displacing fossil fuels which are currently used for load levelling. Conversely, hydrogen from other non-fossil fuel sources could be used by public utilities to generate electricity and fed into the electrical grid. It might even be possible to use hydrogen derived from coal to generate electricity with less coal consumption than if the coal were used directly in a thermal generating plant. According to Kukkonen (1982), coal can be converted to gaseous hydrogen with an efficiency of 0.54 (output energy/input energy), while according to Awad and Veziroglu (1984), fuel cell efficiencies of 80-90 percent may be attainable. Thus, the efficiency of coal to hydrogen to electricity may be 44-48 percent, which is one third greater than the efficiency of 33-35 percent in current coal-fired thermal power plants.

Hydrogen homesteads

Although energy stored in hydrogen can be converted to electricity much more efficiently than energy stored in fossil fuels, energy losses of up to 50 percent but generally of 10-20 percent would still occur in the transmission of electricity from electrical generating stations to user. On the other hand, energy stored in hydrogen could be transported long distances by pipeline with an energy consumption of only a few percent of its energy content, and more cheaply than through the construction of electrical transmission lines (see Section 2.4). Thus, further substantial energy savings would be possible by providing gaseous hydrogen directly to individual homes by pipeline, much as natural gas is currently supplied in some areas. The hydrogen could be directly used for electricity generation, space heating, air conditioning, and could be used in place of natural gas in gas-fueled appliances. The Billings Corporation in the United States has built such a homestead (Billings, 1979). Figure 19 illustrates a possible future hydrogen homestead, in which the family automobile would be refueled at home. Tests of 40 kW phosphoric acid fuel cells in homes and apartments give combined thermal and electrical efficiencies of up to 80 percent, although eventual efficiencies of 85-90 percent are expected (Veziroglu, 1987). As well, a household energy consumption of 70 kWh day^{-1} (which could be expected in developed countries if the electricity were used for climate control and some appliances as well as for lighting) would produce 25 l day^{-1} of distillation quality water. This would be sufficient for household cooking and drinking purposes, would reduce the need for water treatment and public concerns about the adequacy of water treatment in areas of contaminated or polluted water supplies, and would serve as a needed source of water in areas lacking sufficient water.

Catalytic combustion for low temperature heat

Hydrogen has a low ignition energy (0.02 mJ versus 0.3 mJ for natural gas) and, when in contact with a suitable catalytic surface, low temperature (20-400 °C) combustion is possible (HOE Middleton Partners, 1983). This is the preferred technology for generating low temperature heat from hydrogen, and could be used in residential space heaters, cooking devices, and industrial dryers and heaters. Low temperature heat constitutes about 30 percent of total Canadian energy use. Catalytic combustion has a number of advantages: (1) the temperature can be controlled by adjusting the hydrogen feed rate; (2) negligible emissions of NO_x

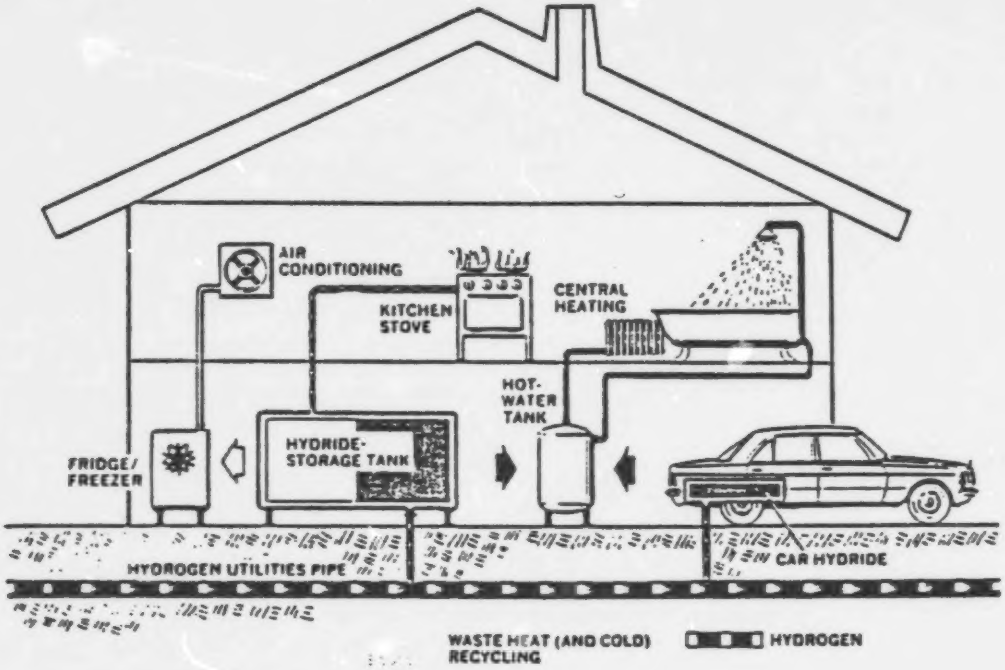
AIR CONDITIONING
KITCHEN STOVE
CENTRAL HEATING
HOT-WATER TANK
HYDRIDE-STORAGE TANK
FRIDGE/ FREEZER
HYDROGEN UTILITIES PIPE
CAR HYDRIDE
WASTE HEAT (AND COLD) RECYCLING
HYDROGEN

Figure 19. Illustration of a hydrogen homestead, taken form Veziroglu (1987).

occur; (3) the system is safe - there is a very low possibility of flashback or explosions; (4) there would be no need for flues or chimneys; and (5) thermal efficiency is very high, exceeding 96 percent for oxide catalysts and exceeding 99 percent for platinum catalysts (Haruto and Sano, 1982a,b).

Industrial generation of electricity

Industries would normally use electricity from the electric utility power grid, but might want to have the capability to generate it locally as a backup power supply, or to make use of waste heat. In the latter case, molten carbonate or solid oxide fuel cells could be used to provide "high quality", high temperature heat where needed (see Table 17).

Power generation at remote sites

In remote communities in Canada diesel generators are used to produce electricity using diesel fuel flown in from outside. Hydrogen fuel would be particularly cost-effective for electricity generation in remote communities because the conversion efficiency is about three times greater than for diesel generators, and the energy content of hydrogen is about three times greater than that of diesel fuel per unit weight (Taylor, 1984). Thus, about 10 times less fuel by weight would be needed using hydrogen, giving a comparable reduction in air transport costs. Remote communities in Canada are thus likely to be among the first places where it will be more economical to use hydrogen rather than fossil fuels to generate electricity. Other advantages of particular value to remote communities include (1) production of pure water as a bi-product, (2) no noise, and (3) the modular nature of fuel cells.

Automotive vehicles

Hydrogen can be used to power automobiles either in internal combustion engines or with a fuel cell. The current thermal efficiency for gasoline powered subcompact cars is about 12 percent, whereas an efficiency of 15 percent (25 percent greater) can be obtained using hydrogen in internal combustion engines. With fuel cells, efficiencies of 45-55 percent can be attained- 4-5 times that of conventional gasoline powered cars (Kukkonen, 1982). Two methods of onboard hydrogen storage are possible: as liquid hydrogen, and as metal hydrides. Hydrogen density is greater as a metal hydride than as a liquid, but there is a strong weight penalty with metal hydrides. Work is underway to develop lighter metal hydride storage systems. For safety reasons, metal hydride storage systems are thought to be more likely than liquid storage; metal hydride storage systems, however, require clean (non-fossil fuel derived) hydrogen as they cannot tolerate impurities such as O_2 and S (Gupta, 1983). Prototype hydrogen fueled automobiles have been developed and tested in a number of countries, and the latest vehicles have performance characteristics (range, maximum speed, acceleration) comparable to gasoline fueled automobiles (Stewart, 1986). As summarized by Stewart (1986),

> "Steady, but slow, progress is being made in the development of hydrogen as a vehicular fuel... With the present availability of hydrocarbon fuels, it does not appear that there will be any large increase in the use of hydrogen as a vehicular fuel. However, as illustrated by the widespread activities in this effort, and the continued interest expressed by the public, research and development will continue, and experience will be gathered leading to the optimization of the use of hydrogen as a vehicular fuel. This will permit a more rapid transition to hydrogen should present conditions change."

Methanol from H_2 and atmospheric CO_2?

Methanol is currently manufactured using one of two chemical reactions:

$$2H_2 + CO \rightarrow CH_3OH + H_2O$$

or

$$3H_2 + CO_2 \rightarrow CH_3OH + H_2O$$

Both the H_2 and CO or CO_2 used in methanol manufacture are presently derived from fossil fuels. Use of outside H_2 in a methanol plant would, according to Blazek et al (1986), permit a doubling of the capacity of existing methanol plants with only 50 percent additional capital. If the H_2 were produced from non-fossil fuel sources, then CO_2 emissions would be reduced as well. If, however, methanol could be manufactured using CO_2 from the atmosphere rather than derived from fossil fuels, then there would be no net emission of CO_2 in the production and use of methanol, just as in the direct use of hydrogen. Methanol has the advantage that the existing storage and distribution system for gasoline could be used and for this reason would be a good transitional fuel in the development of a full hydrogen economy. Incentives would still remain for an eventual switch to the direct use of hydrogen in automobiles because (1) methanol is twice as bulky and twice as heavy as gasoline for a given energy content (Hafele, 1981), whereas hydrogen is three times as bulky but only one third as heavy as gasoline for a given energy content; (2) urban air pollution problems would still remain if methanol were used in automobiles; and (3) methanol likely could not be used as efficiently as hydrogen.

Commercial aircraft

Liquid hydrogen (LH_2) can also be used directly as a fuel in commercial aircraft with a number of distinct advantages over Jet A fuel, the special grade of kerosene currently used worldwide for commercial aircraft. Much work has already been done on the design of LH_2 aircraft and fuelling systems. Brewer (1986) compared design characteristics of a 400 passenger aircraft with a 10,000 km range and a cruising speed of Mach 0.85, and using LH_2, liquid methane (LCH_4) and Synjet (synthetic kerosene manufactured from solid fossil fuels) as alternative fuels. Some of the important design characteristics and cost factors for these fuels are summarized in Table 18. It is seen that, at a cost of US\$10.45/GJ LH_2 (1 GJ = 10^9 J), the hydrogen fueled airplane is competitive with other alternative fuels (costs of hydrogen are discussed in Section 2.4). Two emerging technologies, discussed in Brewer (1986), promise to give hydrogen a decisive advantage over other alternative fuels:

(1) the LH_2 cost given in Table 18 includes conventional liquefaction at US\$4.86/GJ. A new technique - magnetic refrigeration- is likely to reduce the cost and energy needed for hydrogen liquefaction by about 50 percent. A 50 percent reduction in liquefaction costs would reduce the DOC (Direct Operating Cost) to 1.03 c/seat-km.

(2) LH_2 has a boiling point of 20.3 °K and a very high specific heat (9.69 J gm^{-1} $°K^{-1}$), so that it can be used as a heat sink with an intermediate fluid such as N_2 to cool parts of the airplane skin to about 155 °K. This in turn would induce laminar flow over the airplane and dramatically reduce drag. This concept is referred to as "laminar flow control" and would not be feasible using LCH_4 or Synjet fuels. The concept, derived theoretically, has been confirmed by a limited number of wind tunnel tests. From cost estimate data presented in Brewer (1986), it is calculated that use of laminar flow control would reduce fuel consumption to 354 kJ/seat-km and that, combined with a 50 percent reduction in liquefaction costs, would reduce the DOC to 0.78 c/seat-km.

The energy consumption figures given in Table 18 are in terms of the energy content of the delivered fuel. To determine the effect of total energy needs of alternative fuels, the energy used to manufacture and deliver the fuels must be considered.

Table 18. Characteristics of a 400 passenger aircraft with a 10,000 km range, a cruising speed of Mach 0.85, and using various alternative fuels as estimated by Brewer (1986). LH_2 - liquid hydrogen, LCH_4 - liquid methane, and Synjet is Jet A fuel manufactured from solid fossil fuels.

	LH_2	LCH_4	Synjet
fuel cost (US$/GJ):	10.45	8.39	8.04
DOC (c/seat-km):	1.18	1.17	1.16
energy use (kJ/seat-km):	637	717	759
airplane cost (10^6 $):	43.4	47.5	44.5

Brewer (1981) estimated the total process energy required to fly a specified mission using the above three fuels manufactured from coal. For subsonic aircraft the estimated relative process energies are: Synjet, 1.0; LCH_4, 0.82, and LH_2, 0.75. For supersonic aircraft the relative process energy for LH_2 is 0.65, while with laminar flow control in subsonic aircraft the relative process energy for LH_2 is estimated here using results from Brewer (1986) to be 0.42. Thus, even if coal is used as an energy source to manufacture hydrogen during the transition to a full hydrogen economy, CO_2 emissions from the air transportation sector will be reduced.

Wilkinson (1983) sums up one airline view of the prospects of LH_2 fueled commercial aircraft as follows:

> "LH_2 gives promise of being a serious candidate for the longer term but there is not yet convincing proof that cheaper seat mile costs could be produced in today's circumstances. This situation could be changed by the realization of laminar flow by surface cooling at subsonic speeds. There is a strong case for a modest programme of carefully aimed research on an international basis to fill the most important gaps in our knowledge on the design of LH_2 fueled aircraft".

Locomotives

Current diesel powered railway locomotives use the diesel fuel to run a generator to produce electricity, which is then used to run the wheel train. Steinberg and Scott (1984) carried out a techno-economic appraisal of using hydrogen in the regional rail transit system for Toronto, and estimated annual fuel consumption for 75,000 miles per year of 3.38 x 10_4 GJ for diesel and 1.71 x 10_4 GJ for LH_2 using fuel cells. Assuming fuel costs of $9.7 per GJ for diesel and $12.1 per GJ for hydrogen fuel in the year 2000 (1980$), they estimated that annual revenue requirements would be comparable for diesel and hydrogen-fuel cell based systems. As discussed below, it may in fact be possible to supply hydrogen at less than the price assumed by Steinberg and Scott (1984), at least in some regions, in which case the hydrogen based system would be more competitive than the current diesel based system. Because the weight penalty of metal hydride storage would not be as severe a constraint as in personal automobiles, and an extensive refueling infrastructure would not be needed, railway locomotives provide an ideal early use of hydrogen fuel cells for transportation. The expertise gained in building and operating hydrogen powered locomotives would aid in the more difficult transition to hydrogen powered personal automobiles.

Underground mining machinery

Much of the heavy machinery used in underground mining is diesel powered, and considerable cost is incurred in removing the poisonous products of diesel fuel combustion from the mine air. Hydrogen used in internal combustion engines (ICE's) results in minor emissions of NO_x and other pollutants from engine wear or lubricating oil combustion, but would be completely non-polluting if used in a fuel cell. Olavson et al (1985) provide a progress report on development of hydrogen-ICE underground mining machinery. This is also likely to be one of the first routine uses of hydrogen fuel.

Metallurgical and chemical uses

Hydrogen can be used in a number of metallurgical and petroleum industries where it is not currently used, such as in the production of steel, fertilizers, and plastics (Bockris, 1980). In the case of steel production, it can be used in place of coke as a reducing agent. That is, one uses

$$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$$

instead of

$$Fe_2O_3 + CO \rightarrow 2Fe + CO_2$$

which eliminates emissions of CO_2. Assuming a cost for electrolytic hydrogen of US$3.78/GJ, Antonioli (1982) finds the hydrogen based reduction process to be marginally competitive with using natural gas at $4.40/GJ.

Methanol and ethanol from biomass

Hydrogen can be used as an external input in the manufacture of methanol and ethanol from biomass and, in so doing, increase yield by several times, thereby increasing the potential contribution of this renewable energy source to total energy needs (Hafele, 1981; Advisory Group on Hydrogen Opportunities, 1987).

2.4 Safety of hydrogen

There is a widespread public feeling that hydrogen is not a safe fuel, arising largely from the Hindenberg accident of 1934. In this accident 62 out of the 97 passengers survived, and those that died did so as a result of jumping to the ground or from burns from the diesel fuel (Brewer, 1981). Hydrogen fires are in fact much less dangerous than fossil fuel fires because hydrogen fires radiate less heat and their combustion product (water) is not poisonous. Analyses indicate that there is a high probability of surviving an airplane crash in which one is not killed by the impact if the airplane is fueled with hydrogen, whereas this is not the case with aircraft using fossil fuel (Brewer, 1981). Similarly, safe systems can be designed and built for the routine use of hydrogen in automobiles (Stewart, 1986) and in homes (Billings, 1979). Kukkonen (1982) states that a hydride storage system in automobiles would be safer than storing gasoline. It should be recalled that when gasoline was first used as an automotive fuel in the U.S. someone was required to walk in front of the vehicle waving a red flag since a dangerous, and highly explosive, commodity was being carried and burnt!

2.5 Hydrogen distribution and storage

Among the available or emerging hydrogen storage options are: (1) Underground storage in porous media such as aquifers or depleted oil or natural gas fields, all of which have been utilized in Europe or the United States; (2) underground storage in salt caverns, which has been used in England; (3) small scale storage as metal hydrides; (4) small scale storage as liquid hydrogen in insulated containers; and (5) storage in glass microspheres. Metal hydride hydrogen storage densities range from

0.08 to 0.10 gm ml^{-1} whereas liquid hydrogen has a density of only 0.07 gm ml^{-1}; metal hydride storage systems are very heavy due to the weight of the metals, with hydrogen constituting only 3.16 to 7.0 percent by weight. Microsphere storage is an emerging technology which may permit an equivalent hydrogen density as in metal hydrides but with less weight. Storage of pressurized gaseous hydrogen is not a competitive option. See Blazek et al (1986) and Veziroglu (1987) for further details.

With regard to transmission of hydrogen, the most economical method over long distances is by pipeline; several hydrogen pipeline systems are already in operation in Europe and the United States (Kelley and Hagler, 1980). The Institute of Gas Technology of Chicago performed a six month test of a natural gas pipeline system using hydrogen, and found that piping and components operated well with no major incompatibilities (Jasionowski et al 1980). Thus, it is likely that much of the existing natural gas distribution system could be used to distribute hydrogen.

The most difficult development of the hydrogen distribution system required in a full hydrogen economy will be the gradual phasing-in of a network of hydrogen refueling stations for automobiles comparable to the existing network of gasoline stations. A number of prototype refueling stations have been built and tested (Stewart, 1986), and it appears that hydrogen refuelling could be done by the general public as safely and conveniently as present gasoline refuelling.

2.6 The economics of hydrogen

According to Blazek et al (1986), 1982 prices for gaseous hydrogen within about 35 km of the production facility ranged from \$146.54/GJ for the first 40,000 SCF purchased per month (or for the first 13.7 GJ/month) down to \$35.14/GJ for purchases of more than $1.5 \times 10_6$ SCF per month (equivalent to 513 GJ/month). These prices are for for small quantities of hydrogen, and what we would like to know is the range of probable costs for hydrogen if produced in large quantity by dedicated facilities, and how these costs compare with alternative fuels. A barrel of oil contains about 6 GJ of energy, so at a price of \$36 per barrel, the cost of oil is only \$6/GJ. There have been many estimates of the possible future costs of hydrogen and of alternative fuels, and this report shall focus on two such estimates.

Table 19 contains estimates by Awad and Veziroglu (1984) of the cost of gaseous and liquid hydrogen in 1984 US\$ as produced from various sources. The cost estimates for liquid hydrogen assume that magnetic refrigeration techniques are used and add 25 percent to the cost of gaseous hydrogen. As seen from Table 19, hydrogen from coal is expected to be the cheapest hydrogen, and

Table 19. Estimated costs (1984 US$/GJ) for hydrogen produced from various energy sources and for synthetic natural gas (SNG) and synthetic gasoline (Syn-Gas) as calculated by Awad and Veziroglu (1984).

Fuel	Gaseous	Liquid
Coal H_2	6.65	8.31
Hydropower H_2	8.92	11.15
Non hydro electrolysis H_2	10.79-14.90	13.49-18.63
OTEC H_2	15.66-21.23	19.58-26.54
SNG	6.86	---
Syn-Gas	---	13.38

Table 20. Estimated effective costs (1984 US$/GJ) for hydrogen produced from various energy sources and for synthetic natural gas (SNG) and synthetic gasoline (Syn-Gas) as calculated by Awad and Veziroglu (1984). Costs of potential CO_2-induced climatic change are not included.

Fuel		Production Cost	Environmental Cost	Efficiency Factor	Effective Cost
SNG		6.86	5.09	1.0	11.95
GH_2	Coal	6.65	2.55	0.74	6.81
	Hydro	8.92	0.00	0.74	6.60
	Other	16.76	0.00	0.74	12.40
Syn-Gas		13.38	7.64	1.0	21.02
LH_2	Coal	8.31	2.55	0.74	8.04
	Hydro	11.15	0.00	0.74	8.25
	Other	20.95	0.00	0.74	15.50

furthermore, to be cheaper than synthetic natural gas or synthetic gasoline (Syn-gas). Bowman and du Plessis (1986) estimate the probable future cost of synthetic oil from coal or tar sands as Cdn$6.7/GJ, which is considerably cheaper than the cheapest hydrogen cost as estimated by Awad and Veziroglu (1984). As previously noted, Brewer (1986) assumed a cost for synthetic jet fuel of $8.04/GJ and for liquid hydrogen of $10.45/GJ, and even at the higher cost for hydrogen, a hydrogen fueled commercial aircraft would be considerably cheaper to operate using laminar flow control.

A proper cost comparison, however, should take into account various externalities which are borne by society as a whole but ultimately appear as increased consumer costs, as well as taking into account differences in the efficiencies with which various fuels can be utilized. Awad and Veziroglu (1984) estimated the economic costs to society of current fossil fuel use arising from medical ailments caused by pollution, reduced worker productivity, fossil fuel related deaths, costs for current emission controls, reduced farm productivity from ozone and acid rain, conservative estimates of other costs of acid rain through its effects on fish and fresh water sources, and the costs of restoring buildings to overcome the effects of pollution. They have not included the potential costs of CO_2-induced climatic change. Nevertheless, they estimate that the current cost of environmental damage caused by use of fossil fuels is about $7.64/GJ (or about $45 per barrel of oil)! In addition to these quantifiable, economic costs, is a whole range of nonquantifiable costs involving the importance we attach to aesthetic considerations, climatic comfort, and the value of health and human (and non-human) life.

Awad and Veziroglu (1984) also computed a mean efficiency gain for hydrogen compared to fossil fuels by considering individual end-use sectors and separate efficiency gains for each end-use. Integrated across all energy end-uses in this way, they computed that 1000 units of end-use fossil energy consumption could be provided by 736 units of hydrogen energy consumption.

Table 20 shows the computed effective costs for various alternative future sources for gaseous and liquid fuels, taking into account environmental costs (except for potential CO_2 effects) and the difference in mean utilization efficiency for fossil fuels and hydrogen. It is seen that coal and hydropower derived hydrogen are estimated to have comparable effective costs, and to be considerably cheaper than synthetic gas or synthetic gasoline. There is a definite environmental advantage in using coal to produce hydrogen rather than synthetic liquids and gases according to the environmental costs given in Table 20, but to chose between coal and non-coal derived hydrogen requires consideration of CO_2 effects according to the effective costs given in Table 20.

Hammerli (1984) attempted to estimate when electrolytic hydrogen using electricity from CANDU (Canadian Deuterium Uranium) nuclear technology would be competitive with hydrogen produced by methane reforming (which is the major source of hydrogen in Canada). Assuming an electricity cost of 2 c/kWh, he estimates that electrolytic hydrogen could be produced at $8.9/GJ (1980 $CDN) using 1983 technology. This is cheaper than the cheapest non-hydro, electrolytic hydrogen as estimated by Awad and Veziroglu (1984) and arises because electricity is comparatively cheap in Canada. The CANDU nuclear technology provides another cost advantage for electrolytic hydrogen: because CANDU nuclear reactors require heavy water, there is a ready market in Canada for heavy water, which can be produced as a bi-product of the electrolytic production of hydrogen by a process called *C*ombined *E*lectrolysis *C*atalytic *E*xchange-*H*eavy *W*ater *P*rocess (CECE-HWP). Hammerli (1984) assigns a net heavy water credit of $1.32/GJ. Another bi-product of electrolysis is oxygen, and Hammerli (1984) assigns an oxygen credit of $1.25/GJ. It may not always be possible to realize the oxygen credit, however, because of the greater cost of transporting oxygen relative to its value than for heavy water. If both credits can be realized, than the cost of electrolytic hydrogen using 1983 technology would be $6.40/GJ (1980 $CDN). At this price, hydrogen could compete with conventional oil at about US $32 per barrel without taking into account environmental costs or the greater efficiency with which hydrogen can be utilized, and would be competitive with the low synthetic oil cost estimates of Bowman and du Plessis (1986), cited above. CANDU electrolytic hydrogen might also be competitive with coal-derived hydrogen.

Finally, Figure 20, taken from Gregory et al (1972), compares transmission costs as a function of distance for electricity and for hydrogen by pipeline. According to this figure, hydrogen is cheaper as an energy carrier than electricity for long distance transport. A more recent analysis by Leeth (1976), summarized in Figure 21, also indicates that energy transmission as hydrogen in pipelines would be cheaper than transmission of electricity in overhead cables. On the other hand, Figure 22, taken from Barnstaple and Petrella (1982), indicates that transmission of hydrogen by pipeline would be about twice as expensive as transmission of electricity with 500 kV lines.

2.7 Environmental costs of a hydrogen economy

A number of environmental costs would be associated with the displacement of fossil fuels with non-fossil fuel derived hydrogen. These costs are identified and evaluated below.

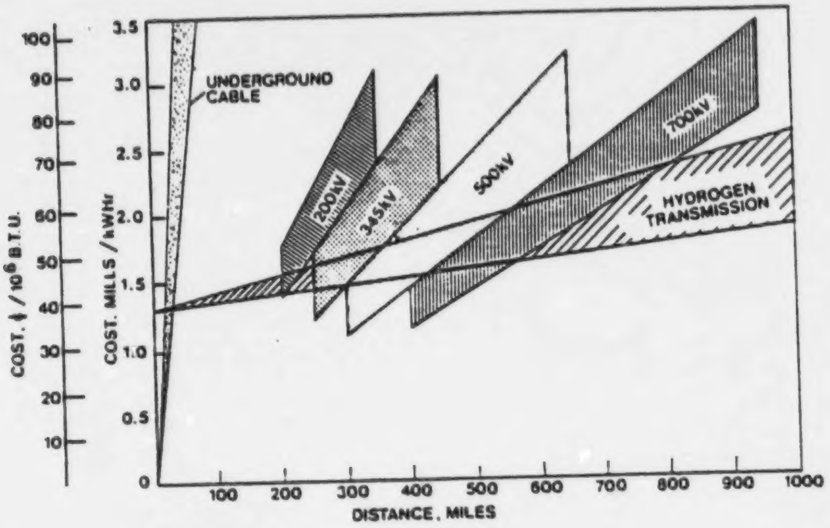

Figure 20. Comparison of costs of transmission of electricity by underground cable and overhead power line, and of transmitting hydrogen by pipeline, as calculated by Gregory et al (1972).

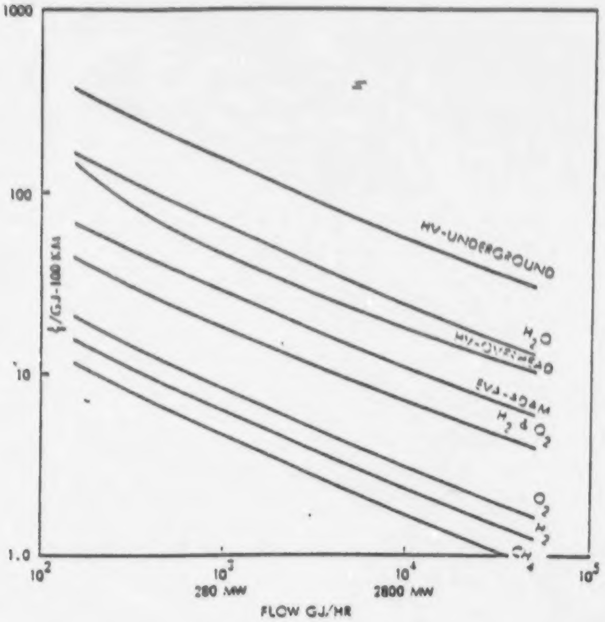

Figure 21. Energy transport costs (1975$) as calculated by Leeth (1976). HV-Overhead = high voltage overhead electrical cables. H_2 is for transmission by pipeline.

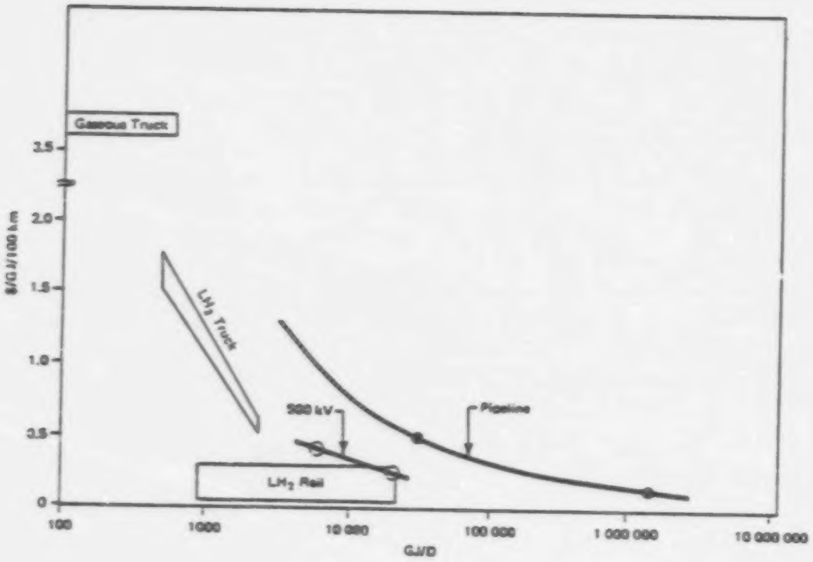

Figure 22. Comparison of costs of transmission of electricity by overhead power line and of hydrogen by pipeline, truck, and rail according to Barnstaple and Petrella (1982).

Production of hydrogen

If hydrogen is produced by electrolysis, then the environmental costs associated with the generation of electricity used to produce hydrogen must be included in the environmental cost of a hydrogen economy. Where nuclear energy is used, the entire nuclear fuel cycle, from extraction of uranium to disposal of wastes and decommissioning of nuclear power plants, must be considered. In the case of hydro-electric power, environmental costs are associated with flooding of land, reduction of river flow and its sediment transporting ability downstream of the dam site, and possible disruption of fish migration and breeding. In the case of solar energy, significant quantities of construction materials will be required, with associated environmental impacts in their extraction and processing. Massive deployment of OTEC energy sources might have a measurable regional effect on surface and subsurface water temperatures in the tropical ocean. Barring a major nuclear accident, all of these effects would be minor or insignificant compared to the effect of continued reliance on fossil fuels.

Electrolysis of water to produce hydrogen also requires water as a feedstock and for cooling. Feedstock water demands would be about 90 x 10^9 l per Gm^3 H_2; this water would have to be purified and, in the case of solid polymer electrolysers, would have to be passed through sand and carbon filters to remove suspended solids and any organic materials, followed by passage through a demineralizer. Regeneration of the demineralizer and cleaning of the filters would generate effluent which could then be treated using commercially available techniques (HOE Middleton Partners, 1983). Water cooling requirements would be about 900 x 10^9 l per Gm^3 H_2, which corresponds to the yearly water demand for a city of 50,000.

Liquefaction of hydrogen would generate waste heat at the rate of about 31 GJ per 100 GJ LH_2, which would have to be dissipated with cooling water (HOE Middleton Partners, 1983). To displace the total Canadian oil consumption of 1.4 million bpd with hydrogen, assuming that half of it would be liquified with the above given rate of waste heat production, and assuming that the coolant water temperature rose 6 °C, then the cooling water requirements for liquefaction would equal that of an urban population of 12 million (i.e.: the domestic water use of about half the population of Canada would be needed to liquify enough hydrogen to displace half of the total oil consumption). Thus, careful attention will be required to avoid excessive thermal pollution. Since the cooling water demands will be non-consumptive, it might be possible to allow a greater temperature increase of the cooling water, dissipate the heat in shallow ponds, and recycle a portion of the coolant.

Storage of hydrogen

Extensive use of metal hydride storage in end-use applications would require increased mining and metallurgical activity, with associated environmental costs. If large amounts of newly-produced hydrogen are stored in depleted oil or gas fields, then residual hydrocarbons may contaminate the hydrogen and may create a water pollution hazard when removed. Natural gas is sometimes stored in this manner; as hydrogen has about one-third the volume energy density of natural gas, the water pollution generated per unit energy stored would be about three times greater.

3. IMPORTANCE OF ENERGY CONSERVATION IN THE TRANSITION TO A HYDROGEN ECONOMY

The global energy consumption in 1975 was about 263 EJ (1 EJ = 10^{18} J). Although there has been a consistent and dramatic downward trend during the last decade in projected future energy consumption rates, conventional analyses of energy growth still project large increases in global energy demand over the next few decades. For example, Edmonds and Reilly (1983) projected an increase in annual global energy consumption to 1646 EJ by the year 2050 using the Institute for Energy Analysis (IEA) model. The projected energy use in 2050 corresponds to an average growth rate from the 1975 base of 2.4 percent per year. The median growth rate of the Edmonds et al (1986) scenarios is 1.7 percent per year for their zero-correlation cases and 1.2 percent per year for their nonzero-correlation cases, and appear to be lower than the Edmonds and Reilly (1983) growth rates primarily as a result of slower economic growth rather than because of greater energy efficiency. In the IIASA "low" growth energy scenario (Hafele, 1981), energy use grows at a rate of 1.7 percent per year. However, Cheng et al (1986) show that making use of all existing technologies to improve the efficiency of energy generation and end use reduces the global energy demand in 2050 to 674.6 EJ for a scenario similar to that of Edmonds and Reilly (1983), which corresponds to a mean energy use growth rate of 1.3 percent per year.

The reduced energy growth projections cited above may very well be unnecessarily high, as Lovins (1980) cites many studies which conclude that global energy use can be maintained at present levels or even decline while still allowing strong economic growth in both the developed and developing countries. In the case of Canada, Robinson (1987b) finds that making use of all currently available, cost-effective technologies would result in energy savings of 50 percent, which would permit total energy demand in Canada to remain at current levels for several decades (by which time new technologies would be available to further improve energy efficiency). Even if the potential energy savings of Robinson (1987b) or Lovins (1980) are too optimistic, improved efficiency of energy generation and end use is still the most cost-effective means available for increasing the effective energy supply, reducing environmental impacts, and slowing down the CO_2 increase until hydrogen fuels begin to displace fossil fuels. Increased use of nuclear energy can not significantly reduce the CO_2 build up over the next few decades for, as stated by Lovins (1980),

> "both IIASA and the Institute for Energy Analysis found that whether or not the world uses nuclear does not make much difference to the date of attaining a particular global CO_2 level. Even the most generous

> nuclear projections ... are too little, too late, against the background of fossil-fuel use rising more slowly but from an enormously greater base. The only important variable in CO_2 timing is energy conservation."

The recently-released Brundtland Commission report (WECD, 1987) also stresses the need for "vigorous promotion of energy-efficient practices in all energy sectors" (pg. 180) irrespectively of whether or not a strongly nuclear energy policy is adopted. The Commission further states that,

> "Fundamental political and institutional shifts are required to restructure investment potential in order to move along these lower, more energy-efficient paths. The Commission believes that there is no other realistic option open to the world for the 21st century... Properly managed, efficiency measures could allow the industrial nations to stabilize their primary energy consumption by the turn of this century" (pp.173-174)

The Brundtland Commission report also states that, "every effort should be made to develop the potential for renewable energy, which should form the foundation of the global energy structure of the 21st century" (pg. 195), but fails to mention hydrogen and its potential in facilitating the use of renewable energy sources by serving as an energy storage medium and as an energy carrier.

This report thus complements the Brundtland Commission report by stressing the important role that hydrogen can play in solving the very environmental problems posed by fossil fuel use which are discussed both here and in the Brundtland Commission report.

It is also clear that energy conservation and the transition to a hydrogen economy complement each other and that both are needed: energy conservation will reduce the rate of CO_2 increase, thereby giving more time to make the transition to a hydrogen economy while keeping CO_2 below a given threshold, and will reduce the total amount of energy which will have to be eventually supplied as hydrogen. On the other hand, use of hydrogen as a fuel, because of the greater efficiency with which it can be utilized, will facilitate the goal of energy conservation.

Finally, it has already been noted that there would be some environmental costs associated with the use of hydrogen. As well, nuclear energy is likely to be an important primary energy source for the production of hydrogen. Energy conservation can play an important role in reducing the environmental impact of hydrogen systems and in reducing the risk associated with nuclear energy by keeping the need for nuclear energy as small as possible.

4. EMERGING POLICY ISSUES

Adaptation versus prevention

Two schools of thought concerning societal and government response to the CO_2 greenhouse effect are (1) to allow the increase to continue as dictated by economic and energy growth, but to attempt to foresee and adapt to the resultant climatic change through breeding of new, more drought resistent crop varieties and of crops more capable of exploiting longer growing seasons, warmer temperatures, and the beneficial direct physiological effects of higher CO_2 concentration; (2) to prevent CO_2 from rising above a given level. Some climatic warming is inevitable (and, indeed, some seems to have already occurred), so adaptation has a definite role to play. On the other hand, recoverable fossil fuel reserves are so large that, sooner or later, deliberate policy steps will have to be taken to limit the CO_2 increase. It is only a question of when. Given that the climatic hazard increases with increasing CO_2, that serious problems of acid rain and urban air pollution will continue as long as we rely on fossil fuels or will be very expensive to solve, and that it will be more difficult and costly to switch to a non-carbon based energy system the longer we wait, it is of the utmost urgence that governments begin now to consider policies designed to slow the increase of CO_2 and to facilitate the transition to a non-carbon based energy system using hydrogen as an energy currency.

CO_2 tax

One possible policy designed to slow the increase of CO_2 and to hasten the transition to a hydrogen economy would be to tax energy sources in proportion to the amount of CO_2 that is emitted to the atmosphere in their manufacture, distribution, and use. Nordhaus and Yohe (1983) explored the effect of a CO_2 tax using a global econometric model and found, for example, that a tax of $10 per ton of coal equivalent energy (1975 US$) had little effect on CO_2 emissions. Taxing energy sources or carriers in direct proportion to the CO_2 emitted in their production and use, however, might have a larger effect, especially when a non-CO_2 emitting alternative is available and is marginally or almost competitive with heavy CO_2 emitters in the absence of a tax. Given the direct cost estimates for hydrogen given in Table 19, this may be necessary in order to favour non-fossil fuel derived hydrogen over hydrogen derived from coal. A policy of taxing CO_2 emissions would likely also favour energy conservation.

Dirty versus clean hydrogen

Hydrogen derived from fossil fuels contains CO_2, CO and S impurities and is referred to as "dirty", whereas electrolytically produced hydrogen is clean, containing no impurities. Clean hydrogen can be used in alkaline fuel cells and metal hydride storage, whereas dirty hydrogen cannot. Alkaline fuel cells would be needed for automotive uses. How hydrogen is produced thus limits its potential applications. In Canada the research funding emphasis is on advancing the date when electrolytic hydrogen will replace fossil-fuel-derived hydrogen. In the U.S. the current fuel cell program is oriented towards using dirty hydrogen from coal to generate electricity. Although this would be better from an environmental point of view than using the coal directly in thermal generating plants, this use of hydrogen would compete with nuclear energy and would tend to encourage further use of coal, thus continuing the increase of atmospheric CO_2. Furthermore, the emphasis in the U.S. has been on fuel cells with operating temperatures in the 600-700 °C range because the CO impurity in dirty hydrogen can act as a fuel at these temperatures (UTME, 1980). Fuel cells with these operating temperatures would not be applicable to transportation uses, where hydrogen could fulfill the requirement for a portable fuel currently satisfied by liquid fossil fuels. For these reasons, the choice between dirty, fossil-fuel derived, and clean, electrolytic, hydrogen is a significant policy issue with regard to the CO_2 increase.

Manufacture of synthetic fuels

Two options are possible with regard to the manufacture of liquid fuels from solids: (1) use of hydrogen derived from gasification of some of the solid fuel itself, which amounts to carbon rejection, or (2) addition of electrolytically produced hydrogen, which reduces the consumption of solid fuels and reduces the CO_2 emission compared to the carbon rejection option. Deliberate policy decisions may be needed to encourage use of the second option. Bowman and du Plessis (1986) recommend providing some of the hydrogen for oil sands development by oxidizing the bitumen residue of oil sands; if CO_2 emissions are to be reduced as much as possible during a transitional phase in which synthetic liquid fuels are used, then this option should be discouraged.

Research funding of solar energy and other renewables

Introduction of hydrogen as an energy carrier greatly expands the potential of solar energy (and other renewable energy sources) in meeting total energy needs by resolving supply-demand mismatch problems, and provides a means by which solar energy could provide a portion of current liquid fuel transportation needs. Solar energy seems particularly promising in the southern

United States, southern Europe, and the desert regions of North Africa and the Middle East, yet support for solar energy research has remained insignificant compared to the support provided for nuclear energy. Although nuclear energy still has an important role to play in some areas, there is much greater justification for increasing the ratio of solar to nuclear research support if hydrogen rather than electricity is the energy carrier.

Private versus government investment

One particularly promising renewable energy source which has been the subject of numerous paper studies but has had little physical testing is Ocean Thermal Energy Conversion (OTEC). The investment needed to start OTEC is probably too great for private industry and the risks too large compared to the potential benefits to the energy industry alone (but not compared to the benefits to society as a whole), so that government involvement is likely needed.

Regional development

In countries such as Canada and the United States, a change from a carbon-based to a hydrogen-based energy system would have implications for regional development. In the case of Canada, it would mean that resources of nonconventional fossil fuels, largely in Alberta and British Columbia, would not be developed, whereas hydro-electric and nuclear generating capacity in Manitoba, Ontario, and Quebec would become the foundation for Canadian energy. On the other hand, agriculture is of comparable importance to the economy of Alberta and other prairie provinces, and the farmers in the prairie provinces may benefit the most from restrictions to the CO_2 increase. In the case of the United States, coal producing states would strongly resist any efforts to restrict the use of coal as they would feel economically threatened. Policies intended to limit the CO_2 buildup would therefore have to specifically address problems of regional inequality, perhaps by providing incentives to locate some of the new manufacturing industries which would arise in a hydrogen economy in regions which would have otherwise supplied fossil fuels.

The need for international consensus and cooperation

International agreement will be needed to limit the CO_2 increase and to make the transition to a hydrogen economy, and international cooperation will be needed to develop the set technologies necessary to fully exploit the opportunities provided by hydrogen.

Implications for research on climatic impacts of CO_2 and carbon cycle modelling

If a preventative-adaptive rather than a solely adaptive policy is adopted in response to the CO_2 increase, then much greater urgency is added to remaining uncertainties regarding the rate of atmospheric CO_2 increase under different emission scenarios, and of climatic effects, because more lead time is most likely required for prevention than for adaptation.

5. SUMMARY

The positive environmental effects of hydrogen substitution are clear: (1) elimination of urban air pollution, (2) provision of a long term solution to the acid rain problem, and (3) slowing down of the CO_2 increase during the transitional phases in the substitution of hydrogen for fossil fuels and later elimination of the component of the CO_2 increase caused by combustion of fossil fuels.

Recoverable fossil fuel resources are large enough to increase atmospheric CO_2 by a factor of 3 to 11. However, significant climatic change would be associated, in equilibrium, with even a CO_2 doubling. Furthermore, once the climate begins to warm in response to a given CO_2 increase, it is possible that a further CO_2 increase may occur as a result of modification to the natural carbon cycle itself, even if anthropogenic CO_2 emissions stop. Removal of CO_2 and burial in the deep ocean is not a practical solution to the problem, except possibly when hydrogen is produced from coal. It is possible that Mankind as a whole could benefit from a CO_2 doubling, but as CO_2 continues to increase the risk of adverse, and probably catastrophic, climatic changes would increase significantly. Burning more than 10 to 30 % of the recoverable fossil fuel reserves is therefore unacceptable on climatic grounds alone. Finally, several other strong greenhouse gases are also increasing, so that to have no more than the equivalent of a CO_2 doubling requires keeping the actual CO_2 concentration to much less than a doubling - 500 ppmv or less.

The economic costs of allowing CO_2 and other trace gases to continue to increase could be staggering, even in today's terms with sizeable discount rates for future costs. Given that 100's of millions of people could die as a result of disruptions in the global food system, and that the resulting global instability could increase the likelihood of a major war, it seems pointless to try to quantify the economic costs of allowing CO_2 to increase indefinitely. What is clear is that we must not allow this to happen, that allowing the equivalent of a CO_2 doubling may have a net positive effect, that the actual CO_2 increase should nevertheless be kept as small as possible, and that to do so will require initiation of a global plan of action by the end of this century, and therefore that the research to develop such a plan and the evolution of the plan itself must start immediately.

Given the certainty that costs of conventional fossil fuels and of synthetic liquid fuels will rise in the long term as supplies of the higher quality and most easily extractable fuels are exhausted, economic considerations alone will (1) spur the development of increasingly more efficient methods of energy generation and end use using existing energy sources, and (2) motivate the search for more efficient forms of energy. Hydrogen derived from sustainable energy sources promises to be considerably more efficient than conventional liquid fuels for transportation, electricity generation, and heating, and so is a natural choice to replace liquid fuels. Government incentives and increased support for hydrogen related research could hasten the transition to hydrogen, bringing about earlier environmental and health benefits. Furthermore, development of a hydrogen energy system and the associated technologies will create new jobs and generate new wealth in the resource industries, electricity generation and distribution, and in new manufacturing industries.

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